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STREAMS AND THEIR SIGNIFICANCE

DOUGLAS JOHNSON
Columbia University

ABSTRACT

In the following pages there is presented (*a*) a review of the classification of streams according to stages of development, in which the criteria for discriminating different stages are discussed, and some misconceptions regarding stream behavior are corrected. (*b*) The classification of streams according to genesis is then considered, and an attempt made to define with greater precision certain terms regarding the significance of which differences of opinion appear to exist. (*c*) The classifications of streams with respect to genetically associated structures, and (*d*) with respect to structures not concerned with the origin of the streams, are more concisely presented, as is also (*e*) the classification of streams with respect to past changes of level. (*f*) Drainage patterns are briefly referred to, but the discussion of this subject is left to a companion paper subsequent to this article in the *Journal of Geology*.

INTRODUCTION

The members of a complex drainage system may record many events in the past geologic history of a region, some recent and trivial, others ancient and of major importance. It is, therefore, important that the student of geomorphology should give more than passing attention to streams and their significance. The literature of the subject is voluminous, and any adequate treatment of its contents would require a comprehensive volume. The purpose of this paper is much more modest. Instead of reviewing and analyzing the progress of our knowledge concerning streams and their behavior, and in the light of such review proposing a full and consistent treatment of the subject, it is intended in these pages to set forth quite briefly some general conceptions which the writer has been in the habit of placing

before his students each year as a sort of introduction to the more detailed study of streams. The reader will, of course, recognize in what follows much that is old and familiar; for the conceptions of stream action held today represent the accumulated knowledge of a long past in which the names of Playfair, Philippson, Powell, Davis, and others are landmarks indicating specific stages of progress in our understanding of the work of running water. But if most of what I have to say is the common heritage of present-day students, it is hoped that the manner of its presentation, the comments on disputed points, and certain original contributions will render the whole of some help to others who would know our rivers better. The prevalence of certain misconceptions in the literature of geology and geography suggests that even the mere restatement of some fundamental principles of stream development will not be out of place.

THE CLASSIFICATION OF STREAMS

One may classify streams according to a variety of different principles. Depending on the purpose in view, the classification may be according to (*a*) stage of development in the cycle, (*b*) method of origin, or genesis, (*c*) relation to genetically associated structures, (*d*) relation to foreign structures, (*e*) relation to past changes of level, (*f*) pattern of the drainage lines. Given a hundred streams, all might find an appropriate place under most of these six methods of grouping; but in each case any particular stream might find itself grouped with an entirely different set of individuals. For the methods of classification, while indirectly related in some cases, are in their essence mutually independent.

STAGES OF STREAM DEVELOPMENT

Classification of streams according to stages of development into young, sub-mature, mature, late-mature, and old streams is a common procedure, but there is some disagreement regarding the significance of each age term, and regarding the essential criteria for distinguishing different stages and substages of development. The trouble arises in part from early failure to distinguish clearly between the stage of the landmass being dissected by streams, and the stage of the streams accomplishing that dissection. A certain part

of the Allegheny Plateau in West Virginia has been called a "mature region." The term is ambiguous, for the "region" consists, as far as surface form is concerned, of the slopes of countless narrow, steep-sided valleys, many of which are still in their youth. But the stage of the plateau, the thing being dissected, may properly be designated as mature. It will help toward clarity of understanding and expression if one remembers that we may have young valleys in a mature plateau, and mature valleys in a young plateau, just as well as mature valleys in a mature plateau, or young valleys in a young plateau. In other words, there is no necessary relation between stage of landmass dissection and stage of streams dissecting that landmass.

It will be noted that I have used the terms "young valley" and "young stream" interchangeably. This is because the stream, which consists of both water and waste streaming toward the sea, cannot profitably be treated as independent of the depression caused by the streaming water and waste. Depressions not due to stream action, such for example as synclinal troughs and fault-block basins, are better classified as basins and not as valleys, although the geomorphologist recognizes that the uninitiated will continue to speak of the "Great Valley" of California. This will not worry him any more than it worries the astronomer when the man in the street continues to speak of the planets as "stars," but refuses to think of our sun as a star.

Criteria for discriminating stages.—The criteria for discriminating stages of stream development are matters of much importance. When two textbooks can figure exactly similar valleys, one labeled "young valley" and the other "mature valley," it behooves the student to give thought to this problem. It has seemed to the writer that there would be less disagreement in current usage if greater emphasis were placed upon the outstanding events of a stream's life-history.

What are these events? The elimination of lakes, by the combined processes of deposition of sediment to raise the floor of the basin and down-cutting of the outlet to lower the lake level, takes place rather rapidly under normal conditions. The stream now changes from a chain of beadlike expanses of water connected by segments of thread-

like current, to a continuous thread of water. Falls and rapids are the opposites of lakes; for just as the latter occur where the longitudinal profile slopes too steeply upstream, so falls and rapids occur where this profile slopes too steeply downstream. The elimination of these last irregularities of the profile normally proceeds more slowly than the elimination of lakes, while new falls and rapids may develop as streams cut rapidly downward into diverse rock structures. Yet the elimination of falls and rapids may for the most part be accomplished before the slower down-cutting of later time brings the stream to the perfect profile next to be discussed.

Significance of the profile of equilibrium.—The establishment of the profile of equilibrium, when approximately perfect balance is reached between the capacity of the stream for work and the work given the stream to do, is beyond all question the most important event in the life-history of any stream. It is comparable in importance to the passing of adolescence in man, the most important event in the life of the human being. And just as in man adolescence marks the transition from youth to maturity, so we may best accept the establishment of the profile of equilibrium in a stream as marking the passage from its youth to its maturity. Prior to this time the proportion of down-cutting to lateral corrasion has been great; so great in fact that the effect of lateral corrasion is commonly not prominently registered in the valley form, unless it be as a greater or less asymmetry of valley slopes. Hereafter the proportion of down-cutting to lateral corrasion will be so small that the effect of the former may escape attention, while lateral corrasion becomes apparent in the opening out of a valley floor of progressively increasing breadth.

The contrast in conditions just sketched has been responsible for a widespread misconception, frequently encountered in the literature in some such form as the following: "The stream now ceases to cut down, and begins to cut laterally." While the first part of the quoted statement may be true temporarily, it is not true as a generality, and hence is misleading. But the error involved in the phrase "and begins to cut laterally" implies a more serious and fundamental misconception of stream processes. Lateral cutting is at a maximum during the early stages of stream development, when the current is

most vigorous and provided with the most effective cutting tools. Normally the lateral migration of a stream will always exceed its vertical incision, in youth as well as in maturity and old age. This will be true, not only for the outsides of particular bends, but for the stream course as a whole, due to the fact that the bends, like meanders, sweep downstream. Exceptional chasms, where for special reasons and for a short time vertical cutting undoubtedly has exceeded lateral cutting, should not blind us to the more usual conditions. Neither should the fact that the stream in Figure 1 has a narrow, steep-sided valley cause us to lose sight of the fact that in

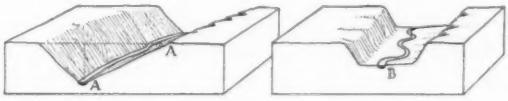

FIG. 1

FIG. 2

sinking its course from A to A' it has cut laterally twice as great a distance as it has cut vertically; and has cut laterally much more than stream B, Figure 2, which possesses an open valley floor.

It is the *proportion* of vertical to lateral cutting which undergoes such a far-reaching change when the stream reaches equilibrium. Lateral cutting is henceforth slightly less effective than formerly; but vertical cutting is enormously reduced. This is why the effect of lateral cutting now first becomes prominent in the production of a relatively flat valley floor. The beginnings of such a floor, with its floodplain cover, afford evidence that the profile of equilibrium has at last been established.

Significance of valley width.—What is the next important change in the river's history? Obviously it comes when the valley floor has been broadened until the stream can freely develop meanders appropriate to its volume. We express this by saying that the valley has acquired a width equal to the width of its normal meander belt, which in turn is ordinarily from ten to twenty times the width of the stream itself. From now on the stream is free to meander at will on its floodplain; but the meander belt as a whole is restrained from shifting its position freely until continued lateral corrasion has given the valley a width several times greater than the width of the me-

ander belt. With the achievement of this condition the last great change in the river's history has taken place. The meander belt may now shift freely over a broad floodplain, the valley may widen indefinitely, the valley walls may become more gently sloping, the shifting stream may continue slowly to consume its floodplain and to reduce the level of its valley floor, at the same time depositing alluvium at the new levels; but in the normal course of events no such striking changes will again take place as characterized its earlier history. The river has entered the last stage of its evolution, old age.

When attempting to compare valley widths with widths of meander belts as a basis for discriminating stages of development, one encounters the practical difficulty that for certain reasons some streams on broad floodplains do not meander. In such a case it is perhaps fair to estimate the appropriate meander belt as being approximately fifteen times the width of the stream, and to use this imaginary meander belt in the desired comparisons. Experience shows that while the width of a given stream may vary within fairly wide limits, and the meander belt of a given stream similarly varies in width, there is normally an approximate relation between stream volume and stream width, and between stream width and width of meander belt, which enables us to make comparisons, only roughly approximate to be sure, yet sufficient for the purpose in view. One cannot give precise criteria for discriminating stages of development, nor divide stages by clean-cut partitions, whether dealing with a river or with men. Passage from one stage to another is normally a gradual transition, and approximate criteria serve the purpose of making approximate divisions and subdivisions.

"*Misfit streams.*"—From the brief analysis given in the preceding pages it should be evident that there is no limit to the size of valley which a given stream may develop for itself. Given sufficient time, even a small stream may acquire a valley of the greatest width. If the small stream happens to be located on a broad belt of weak rock, it may acquire a valley of enormous proportions, while a great river traversing resistant rocks near by still flows in a narrow gorge. Thus time and rock resistance are two factors which, quite apart from stream volume, play a major rôle in determining valley widths. There is no such thing as a valley's being "too broad to have been

formed by the stream which occupies it." Yet one may count by scores the pages in the literature of geology and geography on which this misconception appears in print. Not infrequently doubtful drainage modifications are predicated on the erroneous assumption that a very small stream cannot have a very broad valley, unless that valley was carved for it by some great stream which has since disappeared. The term "misfit stream" is often wrongly applied to a small stream in a large valley, whereas it can properly apply only to streams the meanders of which are obviously out of harmony—

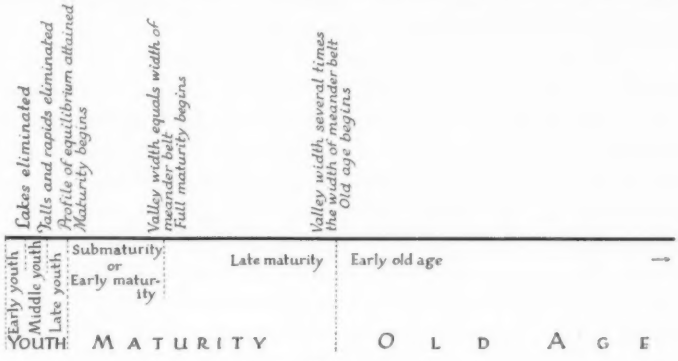

FIG. 3

whether too small or too large—with the meanders of the valley itself, or with meander scarps preserved in the valley wall.

Meander scarps, where these are found with sufficiently large arc of curvature to prove clearly that they represent the dimensions of former stream meanders, and not merely curved cliffs cut during the down-valley migration of shifting bends of smaller size, give us our best indication of former stream volumes. Where these are lacking, one cannot reason directly from size of valley to size of former stream, although one may under certain conditions make deductions based on a comparison of sizes of valleys and sizes of streams where erosion has operated for the same period of time on rocks of the same resistance.

Duration of stages.—If we represent the ideal life-history of any river by a horizontal line as in Figure 3, we may sum up the salient

events in such history, and show their significance as criteria for distinguishing stages of development in the manner portrayed in that figure. It is intended to represent maturity as enduring longer than the stage of youth, and old age as a much longer stage than maturity; but the limits of the page make it impossible to give these differences proper relative values. In terms of percentages of the whole life-history of a river, one might assign 5 per cent to youth, 25 per cent to maturity, and 70 per cent to old age, although this at best is but a scientific guess, designed merely to emphasize the fact that stream evolution proceeds rapidly in its early stages, ever more and more slowly in its later stages.

THE GENESIS OF STREAMS

An anlysis of stream development shows that the various causes of valley locations may be reduced to this simple formula: The position of every valley is determined by inequalities of surface slope, or by inequalities of rock resistance. Valleys falling into the first group might all be termed consequent, those of the second group might all be called subsequent. But such a simple classification does not reveal all that we need to know about the genesis of streams. Hence, further subdivisions have been suggested from time to time, the terminology most employed for this particular classification being that devised by Davis. Not all the terms proposed by him filled a constant need, even in his own writings, and one hears little today of "antogenetic consequents," "complex and compound drainage," and certain other terms appearing in his earlier papers. But some of the concepts elucidated by Davis are indispensable to the student of geomorphology, and no one has ever devised a more acceptable terminology than that proposed by him. We may review the genetic classification of streams and their valleys, making brief comments on some of the terms employed.

Consequent streams.—A stream which has its course determined by, or which is "consequent upon," the initial slope of the land is called a "consequent" stream. In defining such a stream it is fatal to omit the adjective qualifying the noun "slope," as is sometimes done; for merely to say that a stream is "determined by the slope of the land" does little more than tell us that water runs downhill.

Even to specify the "general slope" or "regional slope" is insufficient, since several classes of streams of different origin would be included by so broad a term. One must make clear the fact that by consequent stream is meant a stream which flows or did flow down the initial slope, the original slope, the constructional slope, of the land. If the streams actually take their rise on the initial or constructional slope, as, for example, the radial streams of a volcano or streams born on a newly uplifted coastal plain, they are called "initial consequents." If they are merely extensions, across the initial slope, of streams already existing on an earlier land surface, as in the case of a river in an oldland area flowing out across a recently elevated coastal plain, they are called "extended consequents."[1]

Subsequent streams.—A stream which develops by headward erosion along a belt of weak rock is called a "subsequent" stream. The weak rock belt may be the outcrop of some nonresistant stratum, a dike which is less resistant than the country rock penetrated by it, the crushed zone along a fault, or the weathered zone bordering a joint plane. Notwithstanding the excellent authority for such usage, it is undoubtedly confusing and misleading to define the term "subsequent" as meaning following after, or developed after, the consequent stream. If "subsequent" be employed in geomorphology in the sense of "later in time," it fails to designate any single type of stream, but applies equally to all the other genetic types mentioned below; for all of these normally develop after the consequent drainage is established. The student will best get the conception of the originator of the term, and will keep essential distinctions more clearly in mind, if he will think of a subsequent stream as one which follows along or is *sequent* to the underlying or *sub*structure.

Obsequent streams.—A stream which flows in a direction opposite that of the consequent drainage is called an "obsequent" stream (opposite consequent = op(posite con)sequent = obsequent). The

[1] Miss Charlotte Preuss, graduate student in physiography at Columbia University, has called my attention to the fact that the term "extended consequent" is ambiguous, since it may be taken to imply that the stream was a consequent on the oldland, and has merely been extended across the coastal plain. The objection is valid, since a subsequent or any other genetic type of stream on the oldland may be extended across the newly raised sea-bottom; but I have not found a term which seemed to me sufficiently good to replace the one already in use.

term has occasionally been applied to the "inverted stream" developing after capture; but since all other genetic types of streams, as well as consequent streams, may suffer capture, such usage introduces confusion into what should be, and may be, a clear and logical terminology.

It need hardly be pointed out that, when obsequent streams are said to flow "in the direction opposite that of the consequent drainage," the student must understand that the phrase "in the same area" is by implication a part of the definition. On a slightly tilted fault block mountain (Fig. 4) there is normally a series of long consequent streams, *ab*, descending the gentle backslope of the block. A series of shorter streams, *ac*, flow in the opposite direction, down the fault face; but these are not obsequent streams. They are likewise consequents—consequent on the initial slope of the fault scarp. Later, when these steeper, shorter consequents have pushed the divide, *d* (between them and the opposing consequents), some distance down the backslope of the range, their lengthened upper courses, *ed*, will be truly obsequent, since they will flow in a direction opposite to that in which the consequent drainage "in the same area" formerly flowed.

FIG. 4

Resequent streams.—A stream which flows in a direction identical with that of the consequent drainage, but which develops at a lower level than the initial slope, is called a "resequent" stream. We may think of such a stream as having "retaken a consequent direction" (hence re-consequent = re(con)sequent = resequent). The essential elements in the conception of this stream type are the "renewed" development of drainage in a consequent direction, after other drainage has intervened for a time, and the fact that this renewed development takes place at a *lower horizon* than that on which the drainage initially developed. It is, therefore, not quite sufficient to say that resequent streams are those which flow in the direction of the consequent drainage; for such a definition is broad enough to include both consequents and resequents. Since consequents themselves may persist in initial courses while cutting down to lower levels, or some

parts of consequents may so persist while other parts are lost by capture, it is not safe to regard as a resequent any stream flowing in a consequent direction at a low horizon. We must know that the stream developed at the lower horizon before we can so classify it. In practice it is frequently difficult or impossible to distinguish in particular cases between resequents and inherited consequents, even when we know that there must be many resequents present in the area. But realization of the fact that a stream may be a resequent will often prevent an erroneous interpretation of geomorphic history.

Insequent streams.—Streams the courses of which are not due to (consequent upon) determinable factors are called "insequent" streams (in(con)sequent = insequent). While the term literally means "not consequent," it should not be interpreted to mean any stream which does not belong in the class of consequents. "Not consequent" must here rather be interpreted "not due to." It is essential, also, to complete the phrase by adding "determinable factors," since it is not intended to imply that the courses of these streams are without structural or topographic control. On the contrary, the location of each part of an insequent drainage system was doubtless determined in the first instance by inequalities of surface slope or inequalities of rock resistance. But these inequalities were so slight, or so obscure, or have been so completely effaced by later erosion, that it is not possible, when surveying the irregularly branching stream, to say why it ran this way, or bent in that direction, or branched at those angles. A faint dip in the surface of plain or plateau, an inconspicuous joint plane, a local increase in lime content of a given stratum, may have been sufficient to guide the growing ravine which later became the present valley, such guidance persisting for but a few feet, or a few hundred feet, when some other control perhaps came into play.

Only in the horizontal rocks of a level plain or plateau, or in massive crystallines, which have been planed by earlier erosion, do we ordinarily get that close approach to equality of surface slope and rock resistance in all horizontal directions which permits the best development of insequent drainage. Hence good insequent drainage, like good consequent, subsequent, resequent, and obsequent drain-

age, may tell us something, though not everything, about the original external form and the internal structure of a landmass.

It will appear, on consideration, that in certain geologic structures streams may develop which partake of the characters of more than one of the foregoing genetic types. Thus in Figure 5 if we imagine a stream *CC*, which is consequent on an inclined coastal plain, to be superposed on underlying folded structures, we have no difficulty in recognizing ordinary subsequents *S*,*S*, developed on belts of weak rock. Nor is there any complication about the obsequents *O*,*O*, which flow down the flanks of resistant ridges in directions opposite that of the lateral consequents, the latter having formerly descended the sides of bordering anticlines to join a longitudinal consequent which must originally have flowed toward us in the trough of the pitching syncline. The resequents *R*,*R*, have the directions of the former lateral consequents, although it is obvious that they represent a new development of drainage at a lower level than the original surface of the syncline.

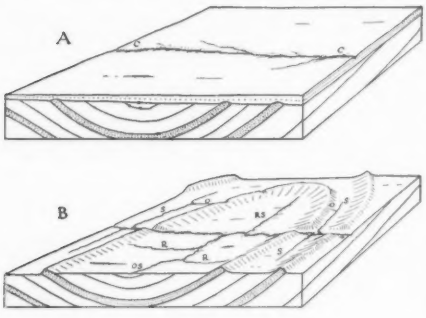

FIG. 5

But when we consider the streams *RS* and *OS* in the center of the eroded syncline, we encounter a new complication. Both of these streams are subsequents, for they have developed by headward erosion along the belt of weak shales in the center of the syncline exposed when the overlying coastal plain beds were stripped off. In addition the stream *RS* is a resequent, for it flows in the same direction as the former longitudinal consequent, referred to above, and has obviously developed at a horizon far below the initial surface of the fold. We may call it a resequent-subsequent. The stream *OS*, flowing in a direction opposite to that of the former longitudinal consequent, is obsequent as well as subsequent, and may be called an obsequent-subsequent stream.

Some may find the foregoing genetic classification of streams too refined for their use. To these the terminology will be confusing, and the task of memorizing the names and their significance will be a burden. Such a task should never be undertaken. The fact that it constitutes a task is sufficient proof that those who find it so do not have serious need for the classification. If a few simple terms such as "longitudinal stream," "transverse stream," "dip-slope stream," or more roundabout descriptive phrases will serve the needs of the geologist or geographer, let such terms suffice for him. But the geomorphologist who deals constantly and intimately with drainage problems cannot do his work with such crude tools. He makes frequent and close acquaintance with streams of diverse genesis, he has a clear image of the typical history of each, and he must have clean-cut, precise terms by which to designate the various types. For him the terminology given above is not confusing, but clarifying; it does not have to be memorized, because it is largely self-explanatory and neatly fits conceptions with which he is already familiar; it is convenient, because it avoids the ambiguity of loose terms of more general application, and the cumbrous circumlocutions of descriptive phrases; and it is practical, for experience teaches him that precise terminology is an aid to that precision of thought which is essential to the successful solution of complicated drainage histories of past geologic time. That some of the terms have been wrongly used is not so much an evidence of inherent lack of precision in the terms themselves, as it is an indication of the need for care on the part of those who employ them.

RELATIONS OF STREAMS TO GENETICALLY ASSOCIATED STRUCTURES

We often find it convenient to employ a simple classification of stream valleys based on their relations to the geological structures with which their development was associated. Longitudinal or strike valleys, parallel to the well-marked structural belts of a tilted or folded region, may be "monoclinal" valleys, "anticlinal" valleys, or "synclinal" valleys. In the first two cases the streams will normally be subsequents; in the last case they may be consequents, resequent-subsequents, or obsequent-subsequents. Transverse valleys have

been called "cataclinal" where the direction of stream flow is in the direction of the dip, as is the case with consequents and resequents; and "anaclinal" where the direction of flow is against the dip, as in the case of obsequents. The last two terms are less commonly employed than are the other three, possibly in part because the terms "consequent," "resequent," and "obsequent" indicate relation to dip and at the same time convey additional information about the origin of the valleys; and perhaps also in part because the terms "cataclinal" and "anaclinal" are less significant than the others, applying as they do to many streams belonging in some of the classes considered below.

Valleys which have their locations determined by faults are called "fault" valleys if the stream is consequent on the faulted surface, "fault-line" valleys if the stream develops as a subsequent, either on the crushed zone or on an infaulted strip of weaker rock. "Joint" valleys may develop as subsequents along weakened joint planes.

RELATIONS OF STREAMS TO FOREIGN STRUCTURES

It was early recognized that a distinction must be made between streams genetically related to the structures on which they flow, and streams which traverse structures quite foreign to those on which they originated. Streams of the latter group are divided into two main classes: those in which the stream course antedates the foreign structure, and those in which the foreign structure antedates the stream course. In the first case a stream of any genetic type, developing in response to any given geological structure, may at some time in its history have a new and wholly extraneous structure developed across its course. The new structure, quite foreign to that which guided the stream's development, may be a gradually growing anticline, a slowly down-warped basin, or an uplifted fault block. If the stream is able to maintain its original course despite the growing obstacle, it is called an "antecedent" stream, because it acquired its course antecedent to the development of the new structure.

The reverse situation occurs when the foreign structure is already

in existence, but blanked by overlying deposits on which streams acquire courses in harmony with the constructional surface or internal structures of the overlying formation. If, later, these streams cut through the overlying deposits, and thus have their courses "imposed from above" upon the underlying structure, such streams are called "superimposed," or more simply "superposed." We may speak of superposed consequents, superposed subsequents, and so on, provided we keep clearly in mind that the words "consequent," "subsequent," etc., refer to the stream's genetic relation to the overlying beds, whereas the word "superposed" in each case refers to the same stream's relation to the underlying structures, wholly foreign to the stream's normal evolution. In Figure 5 the transverse master stream is a superposed consequent; consequent upon the constructional slope of the coastal plain which buried the beveled fold, and superposed upon the underlying syncline, a structure quite foreign to that which determined the genesis of the stream.

Not infrequently the term "superimposed" (or "superposed") has been broadened to include streams let down upon lower parts of the very same structure that determined the genesis of the stream. Thus a subsequent stream entrenched in a resistant underlying stratum of the coastal plain on which the stream originated, a radial consequent incised in the core of the laccolith upon which the stream took its rise, and a horseshoe-shaped subsequent stranded across the nose of a hard layer plunging underground at the end of an anticline have all been called "superimposed streams." It is true that in each of these cases the stream has been "let down from above" upon underlying beds. But if incision from above be made the sole criterion of a superposed stream, the term becomes so broad as to include most streams, and so becomes practically meaningless. It is better to speak of the streams in question as having "inherited" consequent or subsequent courses from higher levels, and to restrict the term "superposed" to streams imposed upon foreign structures. It may help us to keep the desired distinction in mind if we think of inheritance as something normally taking place within the family, while imposition from above implies something outside the normal course of events.

RELATIONS OF STREAMS TO PAST CHANGES OF LEVEL

Where regional uplift or depression, or both, have taken place, it is desirable to classify those streams which show the effects of either change of level. Uplift causes renewed incision of streams, often with such accompanying changes as the development of falls and rapids, an inner gorge, rock benches or terraces, incised or entrenched meanders, and certain less striking features. Such a stream is said to be *rejuvenated* or revived. As the latter term has been used in a slightly different sense, for streams not now showing evidence of the uplift, it is perhaps wiser to employ the former term. It should further be noted that depression of one part of a continent with respect to another which remains quiescent; or depression of both parts, but of one part more than the other; or a drop in sea level with no change in land level, may all cause stream incision in certain areas, with the production of the associated phenomena described above. The term "rejuvenation" is satisfactory, because it connotes the change in the stream's condition without implying the nature of the change of level, or even what it was that changed.

Depression of the land, or rise of sea level, causes the lower parts of valleys near the coast to be invaded by the sea. A stream which has suffered this history is said to be *drowned*. If the influx of fresh water be great, the upper parts of the drowned area may be fresh instead of salt; and if bars separate the drowned valley from the open ocean, as in Pamlico and Albemarle Sound, most of the drowned area may contain water which is fresh or only brackish.

One defect of this classification remains to be noted. The term "rejuvenated" applies not alone to streams affected by changes of level but to streams which experience similar alterations in character due to changes of climate, stream piracy, and certain other events. There is no satisfactory term indicating rejuvenation due to changes of level alone; and even if there were, we should be confronted by the awkward fact that in the present state of our knowledge it is often impossible to say, for example, whether the streams of a given area owe their rejuvenated characteristics to a change of level or to a change of climate. Perhaps the classification will be improved as our knowledge of the criteria and causes of rejuvenation increases.

DRAINAGE PATTERNS

When we attempt to classify streams according to the patterns they make on the earth's surface, we have to discriminate between the patterns of individual streams, which may be *irregular*, *meandering*, *misfit meandering*, *rectilinear*, *braided*, and so on, and the patterns of stream systems, which may be *parallel*, *dendritic*, *rectangular*, *trellis*, *radial*, or *annular*, to mention only the more common classes of drainage patterns. It is this second group of patterns which is most significant for the geomorphologist. Its importance is so great that it deserves special treatment, which is given in a companion paper to the present discussion (article following), prepared at my suggestion by Miss Emilie R. Zernitz, formerly research assistant in physiography at Columbia University.

DRAINAGE PATTERNS AND THEIR SIGNIFICANCE[1]

EMILIE R. ZERNITZ
Columbia University

ABSTRACT

A study of the patterns assumed by drainage lines suggests the existence of types additional to those commonly recognized. A more detailed classification of drainage patterns is herewith presented, in the belief that clearer conceptions regarding the various types will increase their usefulness in interpreting structural controls of drainage evolution.

INTRODUCTION

The patterns which streams form are determined by inequalities of surface slope and inequalities of rock resistance. This being true, it is evident that drainage patterns may reflect original slope and original structure or the successive episodes by which the surface has been modified, including uplift, depression, tilting, warping, folding, faulting, and jointing, as well as deposition by the sea, glaciers, volcanoes, winds, and rivers. A single drainage pattern may be the result of one or of several of these factors. Moreover, as streams are long lived, comprising among physiographic features "some of the oldest survivors or surviving remnants and also some of the youngest developments in response to earth movements," they may embody a long record of the geologic history of a region. As Bailey Willis has well said:

> Those [streams] of an older generation often continue to exist in sections as parts of a younger system, by which they have been captured and dismembered. The direction of flow and the angles in the course thus register older and younger controls which were inherent in the structure of the rocks or due to disturbing earth movements.[2]

Since drainage patterns are the reflection of so many factors, it is evident that they are of very real significance. They form one of the most immediate approaches to an understanding of geologic structure.

[1] Based on an essay prepared under the direction of Professor Douglas Johnson, and submitted in partial fulfilment of requirements for the degree of Master of Arts in Columbia University. The writer is indebted to Professor Johnson for access to his unpublished manuscript notes on drainage patterns.

[2] *Geologic Structures* (New York: McGraw-Hill, 1929), p. 310.

This article is based on a somewhat detailed study of stream patterns with a view to clarifying the fundamental principles of each type. It is believed that clearer conceptions of the different patterns will increase their usefulness as preliminary diagnostic criteria in the interpretation of land forms and geologic structure.

DENDRITIC DRAINAGE

The dendritic drainage pattern (Fig. 1) is characterized by irregular branching in all directions with the tributaries joining the main stream at all angles. The streams are insequent in origin. In the ideal case there are no true consequent streams, for such take their courses in consequence of some obvious initial slope of the land, and just in proportion as slope becomes the controlling factor does the pattern depart from the true dendritic type. Nor can a true dendritic pattern develop where there are marked zones of weakness which determine valley growth by subsequent streams. Only insequent drainage can develop a perfect dendritic pattern. It may happen that some of the tributaries are by chance parallel, but such are mere coincidences and have no significance in the classification of the drainage as a whole.

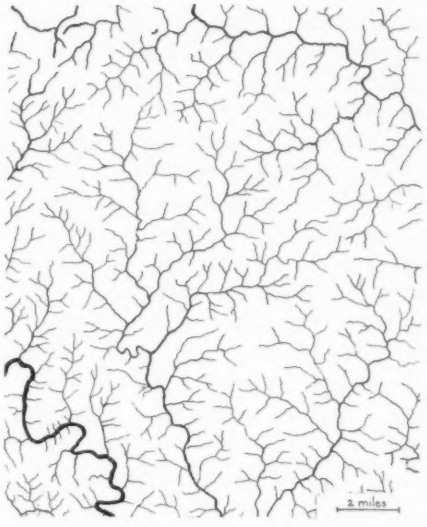

FIG. 1.—Dendritic drainage, northwestern part of Palmyra (Va.) quadrangle. Scale 1:125,000.

The pattern is called "dendritic" because it branches like a tree. This does not mean that the term "dendritic" should be applied to any branching drainage system, for practically all streams branch.

The dendritic pattern may be compared to the branching of an apple tree, while branching that resembles a pine tree or a Lombardy poplar is not dendritic. These latter indicate pronounced structural or slope control, which is lacking in the true dendritic pattern.

Dendritic drainage will develop where rocks offer uniform resistance in a horizontal direction. Such conditions are found in the flat-lying beds of plains and plateaus, and in massive crystalline rocks. The Holden (W.Va.) quadrangle[1] shows typical dendritic drainage in the Allegheny Plateau, while the McCormick (Ga.–S.C.) quadrangle illustrates dendritic drainage in the southern part of the Atlantic coastal plain. The northern third of the Cucamonga (Calif.) and the Mount Washington (N.H.) quadrangles illustrate this drainage on massive crystallines.

Rocks differing in composition but of equal resistance may occur in regions which have suffered intense metamorphism. Original differences in rock hardness tend to be obliterated by metamorphic action, and on such rocks there may develop a pattern that is essentially dendritic. The Mount Monadnock (N.H.) and Chesterfield (Mass.) sheets have been cited as illustrations,[2] but glaciation and the presence of infolded belts of limestone in this and adjacent sections of the highly metamorphosed New England area have led to the development of a drainage pattern that differs so much from the true dendritic as hardly to justify classifying it under that heading. This type of drainage will be later discussed as the complex pattern.

Since dendritic drainage develops as a result of several structural conditions, the structure in any given case cannot be as readily inferred as it can from other drainage patterns. It might suggest horizontal sedimentary rocks, superposed drainage on folded sedimentary rocks of equal resistance, massive igneous rocks, or complex metamorphics. In general, dendritic drainage implies a lack of marked structural control.

An early use of the term "dendritic" occurs in I. C. Russell's

[1] All quadrangles cited in the text refer to topographic maps of the U.S. Geol. Surv. unless otherwise indicated.

[2] Dake and Brown, *Interpretation of Topographic and Geologic Maps* (New York: McGraw-Hill, 1925), pp. 127–28.

Rivers of North America.[1] But the distinctive type of drainage that the term represents was recognized many years before and associated with branching like a tree. In 1882 C. E. Dutton[2] wrote: "Every canyon wall throughout its trunk, branches, and twigs. . . . ." The idea of impartial branching in all directions he expresses thus: "an intricate network, like the fibres of a leaf"; while the drainage system is described as "a minutely ramified plexus of ravines."

The term does not appear to have come into general use in 1895, for Bailey Willis in discussing drainage patterns in the Appalachians at that time referred to this type as one where "the streams flow diversely over rocks which lie in horizontal beds."[3] A year later William Morris Davis wrote: "Regions of essentially horizontal structure normally have wandering streams; no systematic arrangement of drainage is here to be expected."[4] That the concept of dendritic drainage was well understood, however, is shown by the foregoing as well as the following quotation from Davis written in 1895: "Uplifted platforms have therefore, when they rise above the sea, and for some time thereafter, a drainage system that is essentially indifferent to the rock structure."[5] Hobbs,[6] as late as 1899–1900, instead of using the term "dendritic" speaks of "twiglike branches" that are normally produced in homogeneous rocks. It thus appears that the concept of dendritic drainage was widely recognized before the term itself came into general use.

TRELLIS DRAINAGE

The essential characteristic of trellis drainage (Fig. 2) is the presence of secondary tributaries parallel to the master-stream or

[1] New York: G. P. Putnam, 1898), p. 204. "The student should study also the well-developed dendritic drainage in Lebanon Valley."

[2] "The Tertiary History of the Grand Canyon District," *U.S. Geol. Surv. Mon. 2* (1882), pp. 6, 62, 63.

[3] "The Northern Appalachians," *Nat. Geog. Soc. Mon. 1* (1895), p. 186.

[4] "Plains of Marine and Subaerial Denudation," *Bull. Geol. Soc. Amer.*, Vol. VII (1896), p. 398. Reprinted in *Geog. Essays* (Boston: Ginn, 1909), p. 346.

[5] "Physical Geography of Southern New England," *Nat. Geog. Soc. Mon. 1* (1895), p. 277.

[6] W. H. Hobbs, "The Newark System of the Pomperaug Valley, Connecticut," *U.S. Geol. Surv. Ann. Rept. 21*, Part III (1899–1900), p. 145.

other stream into which the primary tributaries enter. These secondary tributaries are usually conspicuously elongated and approximately at right angles to the streams into which they flow. The term "trellis" should not be applied where but one set of tributaries joins a master-stream at right angles,[1] for such may represent the beginning of dendritic or of rectangular drainage; whereas the trellis pattern implies a lattice effect which the elongated parallel secondary tributaries furnish.

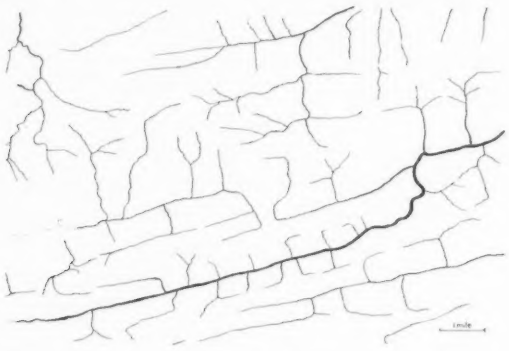

FIG. 2.—Trellis drainage, southern part of Williamsport (Pa.) quadrangle. Scale 1:62,500.

Drainage wholly consequent in origin may assume the trellis pattern as the result of glaciation. In the northeastern part of Geneva (N.Y.) quadrangle the character of the topography is transitional between typical drumlins and fluted ground moraine. Because of the linear alignment of those depositional features, a trellis pattern that is consequent in origin has developed. Consequent trellis drainage is unusual, however. As a rule, trellis drainage is made up mainly of subsequent streams connected by resequents or obsequents, and develops where the edges of formations varying in resistance outcrop in parallel belts. It is therefore characteristic of mountains of folded or tilted strata, and of maturely dissected belted coastal plains. The ridge and valley section of the Appalachians furnishes abundant illustrations of trellis drainage that is largely

[1] Douglas Johnson, unpublished notes on drainage patterns.

subsequent in origin. The Williamsport (Pa.) and Monterey (Va.–W.Va.) quadrangles show particularly fine examples.

Sometimes the tributaries in the trellis pattern do not enter the main stream at right angles. This may happen where they are affected by the general declivity of the land toward the ocean, which, although usually slight, may be sufficient to cause the streams to flow somewhat obliquely. The thousands of minor inequalities which occur in rocks cause sinuosities which are an added factor in preventing right-angled joinings. The Hancock (W.Va.–Pa.) quadrangle shows good trellis drainage where many of the joinings are not right angled.

Bailey Willis in 1895 described the drainage in the Appalachians and referred to it as the "trellis" or "grapevine" system. He wrote: "This arrangement of parallel brooks, which swell the volume of a creek generally flowing at right angles to their courses, resembles a vine from whose central stem branches are trained on a trellis. It is sometimes called the trellis or grapevine system."[1] This is the earliest use of the term in print which the writer has been able to find. It was in common usage, however, in discussion during the preceding decade.[2]

RECTANGULAR DRAINAGE

The rectangular pattern (Fig. 3) is characterized by right-angled bends in both the main stream and its tributaries. It differs from the trellis pattern in that it is more irregular; there is not such perfect parallelism of side streams; these latter are not necessarily as conspicuously elongated; and secondary tributaries need not be present. Structural control is prominent, as the pattern is directly conditioned by the right-angled jointing or faulting of rocks.

Approximate uniformity of fracturing at right angles is characteristic of certain joint systems, and when these determine the pattern of streams, good rectangular drainage results. The evenly spaced, sharp, right-angled turns of Ausable Chasm in northeastern New York, and the occurrence of tributary ravines at approximately uniform distances, is an illustration in point, for here the drainage pat-

[1] *Op. cit.*, p. 187.

[2] Bailey Willis, personal communication.

tern has apparently been determined by joints in the Potsdam sandstone.

The adjustment of drainage in the eastern and southern Adirondacks to lines of weakness developed by faulting was first noted by Kemp, who regarded the valleys as chiefly due to faults. He states: "In many cases these faults afforded a start for lines of drainage which have now worn out the valleys to broad reaches and have masked their origin. The old scarps at present are rounded and worn down."[1] The Elizabethtown (N.Y.) quadrangle exhibits excellent rectangular drainage, somewhat modified by glaciation, owing apparently to two systems of faults intersecting at right angles.

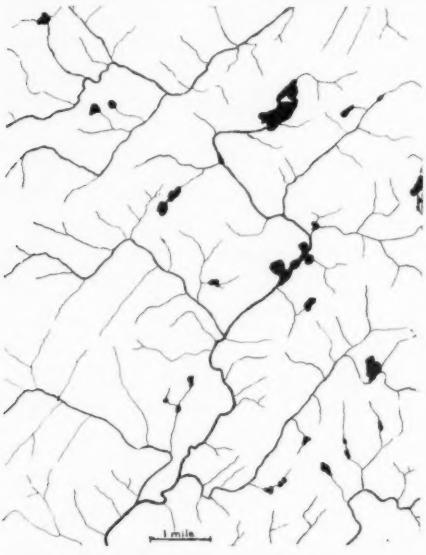

FIG. 3.—Rectangular drainage, southwestern part of Elizabethtown (N.Y.) quadrangle. Scale 1:62,500.

The rectangular drainage of the Adirondacks was first called "trellised,"[2] and was considered as being of the same general pattern as the Appalachian drainage. The sole criterion of the trellis pattern recognized at that time appears to have been the existence of rectangular tributaries, for Davis writes: "When the headwater streams captured the drainage . . . . they developed subsequent rectangular branches growing like a well trained grapevine";[3] while

[1] J. F. Kemp, "Preliminary Report on the Geology of Essex County," *New York State Mus. Ann. Rept. 47* (1894), pp. 632, 634.

[2] A. P. Brigham, "Note on Trellised Drainage in the Adirondacks," *Amer. Geologist*, Vol. XXI (1898), p. 220.

[3] "Rivers and Valleys of Pennsylvania," *Nat. Geog. Mag.*, Vol. I (1889), p. 248; reprinted in *Geog. Essays*, p. 479.

in his "Rivers of Northern New Jersey"[1] he refers to the rectangular courses of the streams that cross the Watchung Mountains and which are part of a trellis pattern. The present classification stresses elongated secondary tributaries parallel to the main stream as the determining factor in differentiating trellis from rectangular drainage, inasmuch as rectangular joinings apply to both patterns.

Rectangular drainage is conspicuously developed along the Norwegian coast, although submergence partially obscures the pattern. The Bergen, Björnör, and Dönna topographic sheets published by the Norwegian Topographic Survey show the rectangular pattern in great detail. Professor Th. Kjerulf, former head of the geological survey of Norway, from a study of the topographic maps came to the conclusion, according to Hobbs,[2] that the bounding lines of the valleys, lakes, and fjords of Norway were almost universally along fault and joint planes. They are, however, not always rectangular. Brögger's field studies in Southern Norway[3] confirmed this generalization for the particular areas studied. He found that the influence of faults and joints upon the formation of the valleys was most profound; in fact, almost every valley and every depression corresponded to a line of dislocation.

The gorge of the Zambesi (Fig. 4), below the famous Victoria Falls, is strikingly rectangular in pattern. A major factor in determining the river's course has been the fractures in the basaltic plateau through which the river flows. The mile-long transverse chasm into which the waters of the falls descend has been scooped out along one of the vertical fractures.[4] These fractures are independent of the columnar jointing characteristic of basalt. The tributaries which drain the basaltic country also make right-angled joinings, owing probably to east and west planes of fracture.[5]

[1] "The Rivers of Northern New Jersey with Notes on the Classification of Rivers in General," *Nat. Geog. Mag.*, Vol. II (1890), p. 99; reprinted in *Geog. Essays*, p. 504.

[2] *Op. cit.*, p. 149.

[3] W. C. Brögger, "Spaltenverwerfungen in der Gegend Langesund-Skien," *Nyt Magazin for Naturvidens kaberne*, Vol. XXVIII (1884), pp. 253–419; "Über die Bildungsgeschichte des Kristianiafjords," *ibid.*, Vol. XXX (1886), pp. 99–231.

[4] G. W. Lamplugh, "Geology of the Zambesi Basin," *Quart. Jour. Geol. Soc. London*, Vol. LXIII (1907), pp. 187–92.

[5] G. W. Lamplugh, "The Gorge of the Zambesi," *Geog. Jour.*, Vol. XXXI (1908), pp. 287–303.

RADIAL DRAINAGE

In radial drainage (Fig. 5) the streams radiate from a central area, like the spokes of a wheel. The consequent drainage of dome mountains is radial, except where an antecedent stream maintains its course across the site of uplift.[1] On more or less circular monadnocks rude radial drainage develops as these residuals assume eminence

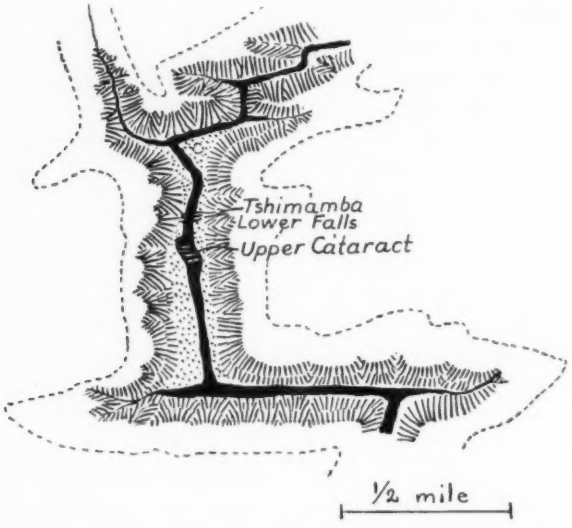

FIG. 4.—Section of gorge of Zambesi below Victoria Falls. (After Lamplugh.) Approximate scale: 1 mile = 2 inches.

through the degradation of the surrounding country. It is the typical consequent drainage pattern of volcanoes, persisting throughout all stages of their life-history. Volcanoes furnish the most perfect examples of this type of drainage pattern, owing to the marked symmetry of form which usually characterizes them and to the conical nature of their internal structures.

All the streams do not necessarily flow away from each other in normal radial pattern. Individual streams may, owing to irregularities in the initial slope of dome or volcano, or to other causes, flow

[1] Dake and Brown, *op. cit.*, p. 134.

for parts of their courses obliquely toward each other; and they may even join. A new lava flow may spread across several valleys and cause those parts of the drainage to unite. As erosion advances some of the streams may become tributaries of their more aggressive neighbors through capture. Gullies may develop on certain valley walls, then grow headward up the slope, and therefore nearly parallel to the main stream. These are all parts of the normal radial pattern.

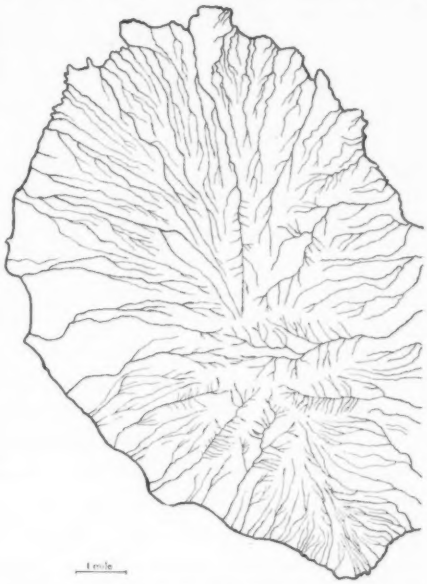

FIG. 5.—Radial drainage, Lahaina (Hawaii) quadrangle. Scale 1:62,500.

Numerous examples of radial drainage on unbreached domes are given in Jaggar's report on the Black Hills.[1] Radial drainage on a monadnock is well shown on the Mount Monadnock (N.H.) quadrangle. Shasta Special (Calif.), Mount Hood (Ore.-Wash.) and Mount Rainier National Park (Wash.) quadrangles, as well as many of the Hawaiian topographic sheets, show excellent radial drainage on volcanoes. Numerous beautiful illustrations are found on maps of the Dutch East Indies.

ANNULAR DRAINAGE

Annular drainage (Fig. 6), as the name implies, is ringlike in pattern. It is subsequent in origin and associated with maturely dissected dome or basin structures.

During the initial stage of dissection of a dome mountain, the

[1] T. A. Jaggar, Jr., "The Laccoliths of the Black Hills," *U.S. Geol. Surv. Ann. Rept. 21*, Part III (1899–1900), pp. 163–303.

streams are consequent in origin and radial in pattern. As erosion advances nonresistant layers are exposed along which subsequent tributaries develop. As these grow in length they reach successive original consequent streams that extend radially down the slopes. By capturing the upper portions of these they increase their own volume and reduce that of the consequent streams. The more fortunate subsequent streams will, furthermore, increase their length at

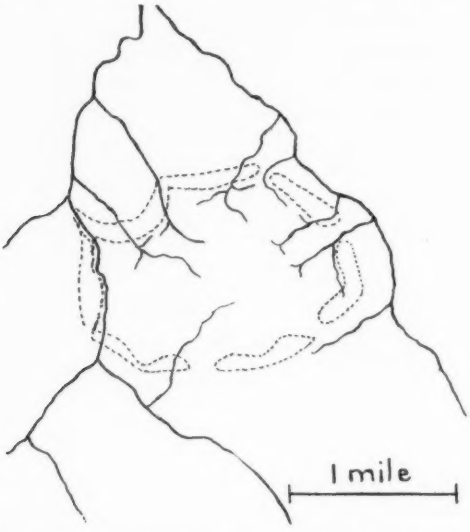

FIG. 6.—Beginnings of annular drainage, Elk Horn Peak, Black Hills. (From *U.S. Geol. Surv. Ann. Rept. 21*, Part III, Pl. XLI, p. 270.)

the expense of less fortunate subsequents as they extend their valleys headward in the weak rock which encircles the dome. Holding their own, in this struggle for survival, will be a few consequent master-streams that have dug channels deeper than those of the piratical subsequents. Thus there results a series of subsequent streams which tend to assume a circular or annular pattern and a few trunk streams which are consequent in origin and radial in pattern.

The annular, like the trellis pattern, is an excellent illustration of the increasing influence of structure over slope as drainage ap-

proaches maturity. Slope alone controls the initial courses of streams; structure and slope, the adjusted courses of maturity. The annular valleys carved out by subsequent streams on domes and basins will be separated from one another by rimming hogbacks, the outcrops of harder strata.

The annular pattern develops most perfectly where erosion of the dome exposes rimming sedimentary strata of greatly varying degrees of hardness. When a thick layer of weak rock is revealed in the central area of the dome, a lowland is there formed. On such a dome the annular pattern may be very poorly or not at all developed, as witness the drainage of Nashville Basin, and that of Little Buffalo and Spring Creek basins on the Meeteetse (Wyo.) quadrangle.

On that excellent example of dome structure, the Black Hills, the most conspicuous member of the annular drainage is the well-known Red Valley, called the "Race Track" by the Indians. It forms a continuous depression encircling the dome and has been etched out of gypsiferous sandy red clays. Minor domes due to local igneous intrusions occur in the Black Hills region. On these, more or less complete annular drainage has developed in many instances. A vivid description of the highly symmetrical and well-developed annular valleys on Inyankara Mountain, one of these minor domes, is quoted by Jaggar from an earlier report and is well worth reading.[1] The domes of the Henry Mountains in Utah, Turkey Mountain on the Watrous (N.M.) quadrangle, and the Wealdan dome in Southeastern England have more or less well-developed annular drainage.

In describing the drainage of the Henry Mountains in 1877, Gilbert showed a clear understanding of initial radial drainage on dome structures when he wrote: "The waterways . . . . formed by the first rain . . . . radiated from the crest in all directions,"[2] but he gave no clear account of annular drainage. Jaggar, in his report on the Black Hills[3] in 1899, used the term "annular valleys" in discussing the erosion of dome mountains.

[1] *Ibid.*, pp. 249–50, 270–71.

[2] G. K. Gilbert, "Geology of the Henry Mountains," *U.S. Geol. and Geog. Surv. of Rocky Mt. Reg.* (1877), p. 145.

[3] *Op. cit.*, pp. 270–74.

PARALLEL DRAINAGE

The drainage pattern is called "parallel" (Fig. 7) when the streams over a considerable area or in a number of successive cases flow nearly parallel to one another. Parallel drainage implies either a pronounced regional slope, or a slope control by parallel topographic features such as glacially remodeled surfaces of the drumloidal or fluted ground moraine type, or control by parallel folded or faulted structures.

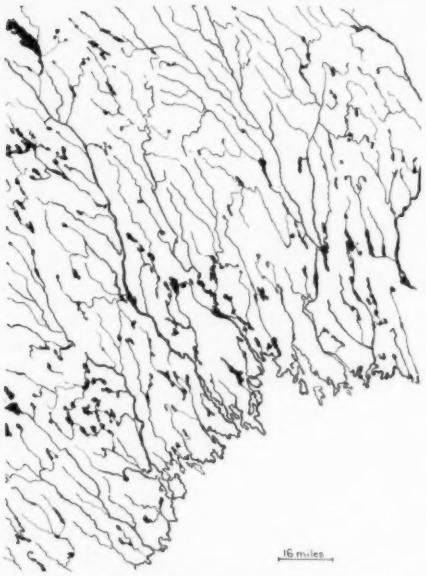

FIG. 7.—Parallel drainage, Northwestern Finland. (Section of Map 3, *Atlas of Finland* [Geog. Soc. of Finland, 1925].) Scale 1:1,000,000.

On newly emerged tilted coastal or lake plains, on the steep slopes of glacial troughs, on the walls of young stream valleys, on lake or sea cliffs, and on fault scarps the stream courses would be controlled by the slope. Such streams would be consequent in origin and parallel in pattern. The glaciated tilted coastal plain in the northwestern part of Finland which borders the Gulf of Bothnia has fairly good parallel drainage, owing to a combination of tilting and glaciation.

On the northern two-thirds of the Highwood (Ill.) quadrangle there is parallel drainage on a slightly dissected lake plain. The streams consequent upon the glacially remodeled slopes of Seneca Lake basin on the Watkins Glen (N.Y.) quadrangle, and many of the streams on the Cloud Peak (Mont.) sheet are illustrations of parallel drainage on the slopes of glacial troughs. On the Kotsima-Kuskulana sheet (Alaska map, No. 601C) are excellent examples of

the same feature. The parallel tributaries involved in the radial drainage pattern on certain volcanoes, as, for example, those of the Lahaina (Hawaii) sheet, have been discussed under radial drainage. Examples of parallel streams on the sides of young valleys can be found on any number of quadrangles representing mature or submature mountains. As dissection advances, the short parallel streams on the face of fault scarps may become parallel canyons. Such are well shown on the western side of the Wasatch Mountains and in some of the Basin ranges.

Numerous parallel streams, subsequent in origin, occur in the folded Appalachians. These are, however, part of the more comprehensive trellis pattern. The parallelism in trellis drainage is in large measure restricted to a parallel relationship between tributaries. In the simple parallel pattern no such relationship is necessary; the parallelism may be between unconnected streams or it may exist between tributaries.

Parallel streams may develop along parallel faults, the streams etching out subsequent valleys along fault zones; or faulting may cause parallel "rift valleys" in which the consequent streams would be parallel.

In the dendritic pattern it is frequently possible to pick out numbers of streams or parts of streams which happen to be parallel. But the significant features of the drainage as a whole, and not the accidental details of selected parts, determine the classification of the pattern. When a stream intrenches its valley rapidly, parallel consequent streams may develop on the valley walls; and when these grow by headward erosion back into the plateau, the lower courses of the elongated streams will be parallel, while the upper courses will be dendritic. The term "parallel drainage" is not commonly applied to the restricted lower portions of such streams, the drainage being classified as a whole under the term "dendritic." This statement applies also to streams originating as parallel gullies on the face of a sea cliff or lake cliff but immediately growing in a variety of directions by headward erosion.

An excellent example of the influence of steep slope in producing parallel gullying is found on the basaltic cliffs of the Hawaiian Islands where the constant trickling of water down the steep faces

of the cliffs has produced remarkably parallel even-spaced depressions which give a fluted appearance to the cliff walls.[1] Jaggar in his drainage experiments observed the importance of uniformity of slope in producing parallelism. He writes: "Lateral tributaries have a tendency to parallelism and rhythmic spacing according as the general slope, initial sheet flood and valley slopes were uniform."[2]

MODIFIED TYPES OF DENDRITIC DRAINAGE

THE PINNATE, SUBDENDRITIC, AND ANASTOMOTIC PATTERNS

In the foregoing pages the six major types of drainage patterns at present commonly recognized have been discussed. These, however, do not include all patterns which streams more or less commonly form. There are additional types which deviate in varying degrees from the established classification.

The greatest diversity occurs in modifications of typical dendritic drainage. We find patterns which resemble the dendritic but which should not be classified as such because the major streams are consequent in origin and show definite slope control. Take, for example, the drainage on the high plains in western South Dakota, western Kansas, and eastern Colorado.[3] It is obvious from the general west-east direction of the major streams and of many of the tributaries that here the slope of the plains largely determines the general direction of the stream courses. The more or less parallel and rhythmical arrangement of the lesser tributaries is doubtless due to uniformity of slope on the sides of major valleys in a region characterized by homogeneity of rock resistance. Acute-angled joinings predominate, indicating a pronounced slope influence. These acute-angled joinings with the rather evenly spaced and parallel tributaries form a pattern so much like that of a feather that it might appropriately be called "pinnate." The Phillipsburg (Kan.) quadrangle illustrates this type of drainage on a larger scale while Figure 8 is an example of pinnate

[1] H. S. Palmer, "Lapies in Hawaiian Basalts," *Geog. Rev.*, Vol. XVII (1927), pp. 627–31.

[2] "Experiments Illustrating Erosion and Sedimentation," *Harvard Coll. Bull. Mus. Comp. Zoöl.*, Vol. XLIX (1908), p. 295.

[3] *Rand McNally Commercial Atlas of America* (55th ed., 1924), pp. 351, 369, 437. Scale: approximately 16 miles = 1 inch.

drainage on a still larger scale. It is a prominent type of drainage in Roumania[1] and Southwestern Persia.[2]

Sometimes the tributaries are more nearly parallel to the main streams than in pinnate drainage and the pattern resembles the Lombardy poplar type of branching. Since in this case parallelism is the dominant feature, this pattern is classified as "subparallel." It is found in certain sections of the high plains, for example, in eastern Colorado.

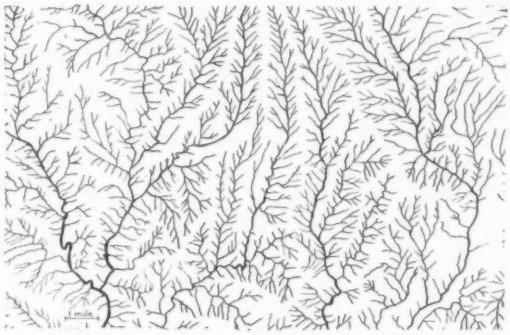

FIG. 8.—Pinnate drainage. (*Sumatra's Westkust geologische Kaart van een gedeelte van Het Gouvernement in 7 Bladen*, ed. R. D. M. Verbeek [1875–79], Blad 5: Solok.) Scale 1: 100,000.

On the Columbus (Ohio) quadrangle the main streams are consequent upon the southward-sloping glacial till plain. As the tributaries of these consequent streams extend horizontally, they encounter rock of homogeneous composition which exerts too slight a structural control to be detected. As dissection advances the slope control of these minor tributaries becomes less pronounced and the drainage tends toward a dendritic pattern; nevertheless, the consequent origin of the major streams continues to be manifest in the north-south direction of their courses. This type of drainage is here designated as "subdendritic" (Fig. 9). It is a rather common variation of typical dendritic drainage.

[1] *Stieler Hand-Atlas* (Gotha: Justus Perthes, 1926–27), pp. 56, 57.

[2] Bushire (Asia—North H39) sheet, *International Map of World* (Roy. Geog. Soc., 1918), 1: 1,000,000.

Flood-plain and delta drainage assumes a characteristic pattern. The tortuous windings of interlocking channels, sloughs, bayous, and oxbow lakes form a network pattern that can be best described as "anastomotic" (Fig. 10).[1] The Mississippi flood plain and delta furnish examples. It is the characteristic drainage over considerable areas of the Hungarian plain and Danubian delta, over the plains of the Indus and Irrawaddy, to cite but a few illustrations. It differs from a braided stream in that it includes features not shown by the latter, as can be seen by comparing the Memphis (Tenn.-Ark.) quadrangle, which shows a section of Mississippi flood-plain drainage, with the Paxton (Neb.) quadrangle upon which the braided Platte River is represented.

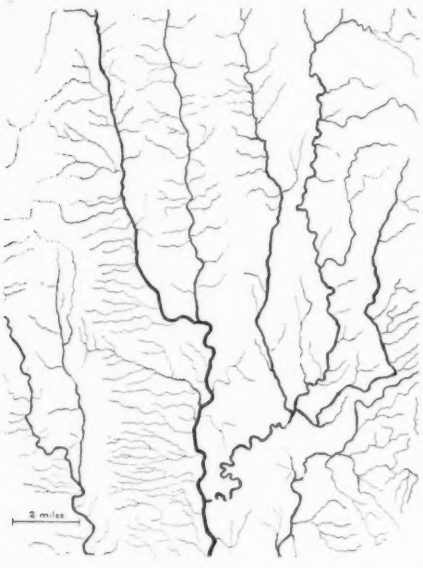

FIG. 9.—Subdendritic drainage, Columbus (Ohio) quadrangle. Scale 1:125,000.

On very flat, youthful coastal plains a network of interlocking streams, swamps, and lakes may occur, as in parts of Florida. The pattern, however, differs from that developed on flood plains. These two varieties of the anastomotic pattern are phases in the development of dendritic drainage, usually in restricted areas.

A MODIFIED TYPE OF TRELLIS DRAINAGE

THE FAULT TRELLIS PATTERN

Trellis drainage may develop where there is a series of parallel faults. These will act as planes of weakness along which erosion

[1] *Anastomotic:* having a network of lines, branches, streams, or the like (Webster's *New International Dictionary*).

readily acts. As a result of faulting, hard and soft layers may be brought into juxtaposition, when lowlands will be developed on the softer layers; or parallel fault valleys may be formed on tilted or down-dropped blocks. Such drainage has been described as "fault trellis" and the San Mateo and Priest Valley (Calif.) quadrangle cited as examples.[1] The spacing between the parallel subsequents is, however, wider than in the typical trellis pattern and the intervening blocks have dendritic drainage. Inasmuch as dendritic drainage is as prominent as fault trellis on these two maps, the drainage as a whole might be better described as complex.

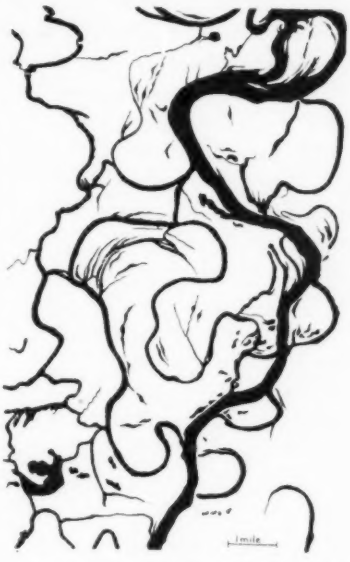

FIG. 10.—Anastomotic drainage. (Section of Apatin und Erdut [Zone 23, Col. XX], *Specialkarte der österreichisch-ungarischen Monarchie* [1905].) Scale 1:75,000.

A MODIFIED TYPE OF RECTANGULAR DRAINAGE

THE ANGULATE PATTERN

All fault or joint-controlled drainage patterns are not necessarily rectangular. Intersecting fault systems might cause an endless variety of stream patterns, depending upon the complexity of the fracturing. Hobbs, who has particularly investigated the influence of faults and joints upon stream courses, attributes to them a far more important rôle than do most students of the subject. He believes the modern school of physiographers ascribes too little importance to structural planes as a factor in determining the position and orientation of water courses.[2] His view is that joints are capillary openings in which water accumulates, and by freezing and by chemical action brings about disintegration. This will produce softer layers on each side of the joint which are easily eroded. Deviations

[1] Dake and Brown, *op. cit.*, pp. 129, 191.

[2] "The River System of Connecticut," *Jour. Geol.*, Vol. IX (1901), pp. 469–85.

from a straight course are believed to be often due to other joint planes crossing the first.[1]

Hobbs, from his researches in the Pomperaug Valley in Connecticut, reached the decision that the faults in the Newark system of rocks controlled the stream patterns in their vicinity; and since the stream courses in the adjacent crystallines were strikingly like those in the Newark, he assumed that the fracture system could be inferred from the drainage, and was therefore the same as that which prevailed in the Newark rocks. The abnormal branching of headwater streams he considered as evidence of several intersecting fault systems. In regard to the rivers about Manhattan Island,[2] he advanced the theory that their channels were largely determined by lines of jointing and displacement. He saw a correspondence between drainage lines and joints in the Driftless Area of Wisconsin,[3] and believed that the striking rectilinear extension and peculiar pattern assumed by the valleys in the Finger Lake district of New York could be explained by structural fractures. His contentions have not, however, been generally accepted.

One of the earliest students of the influence of joints and faults upon drainage was Daubrée,[4] who believed that the development of many river systems was controlled by faults and joints. He explained the parallel arrangement of the main streams and the network of smaller streams in Northern France as due to the existence of a number of sets of intersecting joint planes in the Cretaceous beds of that area, and illustrated his theory with several plates which show the supposed correspondence between the stream courses and the conjectured joints. This region has been cited by Hobbs as an example of joint-controlled drainage.[5] Johnson[6] ex-

[1] E. C. Harder, "The Joint System in the Rocks of Southwestern Wisconsin and Its Relation to the Drainage Network," *Bull. Univ. Wis.*, No. 138, "Sci. Ser.," Vol. III, No. 5 (1906), pp. 207–46.

[2] "Origin of the Channels Surrounding Manhattan Island, New York," *Geol. Soc. Amer. Bull. 16* (1905), pp. 151–82.

[3] "Examples of Joint Controlled Drainage from Wisconsin and New York," *Jour. Geol.*, Vol. XIII (1903), p. 365.

[4] A. Daubrée, *Géologie expérimentale* (Paris: Dunod, 1879), pp. 300–373.

[5] "The Newark System in the Pomperaug Valley, Connecticut," *U.S. Geol. Surv. Ann. Rept. 21*, Part III (1899–1900), p. 146.

[6] Douglas Johnson, *Battlefields of the World War* (London: Oxford University Press, 1921), p. 238.

plains the east-west trend of these particular rivers and their valleys as due to the southward dip of the rocks and to a series of shallow folds that are too faint to be noticeable to the eye but "sufficient to affect the direction of running water and hence the lines of greatest and least erosion."

The influence of joints and fractures upon drainage patterns is likely to be greatly obscured or reduced by the manner in which rocks disintegrate, each rock weathering after its own fashion according to its mineralogical composition and state of aggregation.[1] On the other hand, Jaggar's experiments in producing miniature drainage patterns in the laboratory led him to the conclusion that river patterns are too frequently attributed to the influence of joints and faults.[2]

FIG. 11.—Angulate drainage, northwestern part of Huron-Ottawa territory, Ontario, Canada, 1896. Scale: 5 miles = 1 inch.

Figure 11 illustrates a modification of the rectangular pattern. Parallelism due to faults and joints exists, but the joinings form acute or obtuse angles and not right angles. To call such drainage "rectangular" would be a misnomer, yet it is sufficiently like the latter to warrant a somewhat similar name, hence the term "angulate" is suggested. This drainage pattern is found in the Timiskaming and Nipissing areas of Canada and in parts of Norway.

A MODIFIED TYPE OF RADIAL DRAINAGE

THE CENTRIPETAL OR RADIAL INWARD PATTERN

"Centripetal" or radial inward drainage occurs on the inner slopes of craters and calderas, and where rimming ridges surround basins or valleys as on structural basins or breached domes. Like radial outward drainage, the centripetal drainage of craters and

[1] Geikie, *Earth Sculpture* (London: John Murray, 1898), p. 160.

[2] *Op. cit.*, p. 286.

calderas is consequent in origin. The map of Coon Butte (Fig. 12) is a good example of this pattern, which also is shown on the Sierraville (Calif.) quadrangle. Often the centripetal streams are too insignificant to appear on a map, and one gets the impression that this pattern occurs less frequently than is actually the case. Excellent examples are reported from the Java volcanoes. Davis[1] early used the term "centripetal" in describing radial inward drainage. The streams flowing inward down the slopes of the Tarim Basin in Central Asia are an example of this pattern.[2] Centripetal drainage on structural basins may be consequent or resequent, that on breached domes is obsequent.

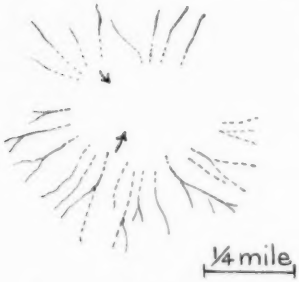

FIG. 12.—Centripetal drainage, Coon Butte, Ariz. Scale 1:30,000.

MODIFIED TYPES OF PARALLEL DRAINAGE

SUBPARALLEL AND COLINEAR DRAINAGE

A drainage pattern which has the streams oriented in a similar direction, but which lacks the regularity of the parallel pattern, may be designated as "subparallel." On the Ramapo (N.Y.–N.J.) quadrangle the streams on the eastern part of the map flow in a general north-south direction, owing to the structure of the beveled Triassic rocks. Figure 13 represents a portion of this drainage. In various parts of New England the schistosity of the rocks, faulting, and complex folding are factors contributing to the development of a subparallel arrangement of many of the streams. This is well shown on a section of the Brookfield (Mass.-Conn.) quadrangle.

Subparallelism between streams may be due to slope control. As previously stated, in some cases this gives a Lombardy-poplar pattern to the drainage. In regions of high relief, steep slopes of major valleys frequently give a subparallel if not a parallel pattern to the tributaries. Sometimes the drainage of a glaciated region assumes a

[1] "Rivers and Valleys of Pennsylvania," *Nat. Geog. Mag.*, Vol. I (1889), p. 249. Reprinted in *Geog. Essays*, p. 479.

[2] *Stielers Hand-Atlas*, p. 69.

subparallel pattern, owing to the linear arrangement of the glacial deposits. The north-south trend of the drumlins on the Weedsport (N.Y.) sheet has caused a subparallel alignment of the streams.

An interesting pattern is found in the region west of Budapest, Hungary, and in the Yang-Yang and Louga areas, Senegal, West Africa, which might be called "colinear" (Fig. 14), since it consists of a succession of streams extending along the same straight line. West of Budapest the streams flow in very straight lines, disappear and emerge again farther on in the same straight line. This is a region of loess and sand, and the wind forms furrows in the easily blown material. These furrows direct the courses of the streams. The permeable nature of the loess and sand causes the streams to disappear where the water table becomes low and to reappear where it again reaches the surface. In the Senegal area many of the streams are intermittent, as the area is a desert; but they are unusually straight and markedly colinear in pattern. The sand, as in the Budapest area, is easily blown into furrows or elongated dunes be-

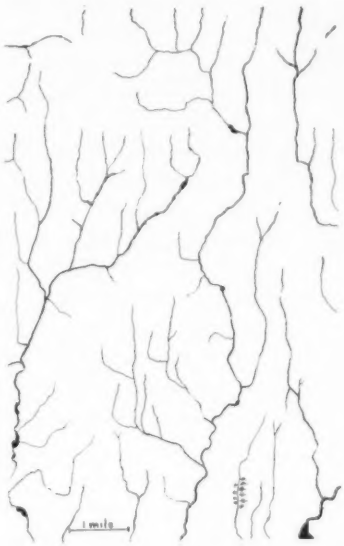

FIG. 13.—Subparallel drainage, eastern part of Ramapo (N.Y.–N.J.) quadrangle. Scale 1: 62,500.

FIG. 14.—Colinear drainage, Senegal, West Africa. (Eastern part of Louga sheet [D28, XX], *Carte régulière* [Afrique Occid'le Française].) Scale 1: 200,000.

tween which streams flow after infrequent but heavy rain storms. The uniform composition of the sandy surface and the torrential character of the temporary streams are additional factors in causing the very straight courses. Colinear drainage is usually part of a larger parallel pattern, but its peculiar character justifies treating it separately.

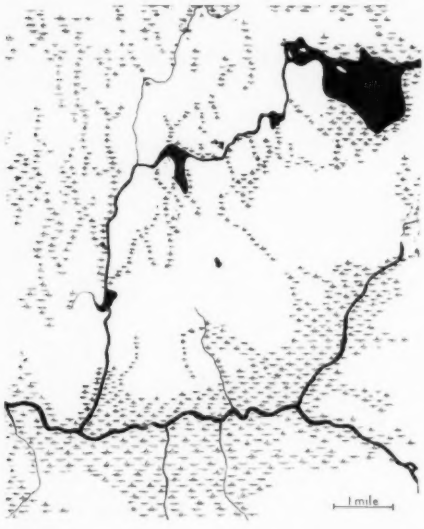

FIG. 15.—Glacially disturbed drainage, section of northern part of Whitewater (Wis.) quadrangle. Scale 1:62,500.

IRREGULAR AND COMPLEX DRAINAGE

Glaciated regions frequently exhibit a distinctive irregular drainage pattern. In such areas a lack of relationship between the stream courses and the higher lands is usually apparent. Streams may exist without valleys. Abandoned valleys may point to stream diversion. Numerous lakes and swamps may testify to the undeveloped character of the drainage. Glacial deposits may more or less completely obscure the hard rock surface. In a word, the former surface has been glacially remodeled, the preglacial drainage effaced, and a new drainage system which bears no relation to the underlying structure has been developed on the new topography. Such conditions exist where the retreat of the ice has been relatively recent, and thus are found in many areas covered by the last or Wisconsin ice sheet.

Such terms as "deranged" or "glacially superimposed" might be used for this "glacially disturbed" drainage pattern (Fig. 15), but the latter term is less cumbersome than "glacially superimposed" and suggests the type better than does "deranged." Its wide distri-

bution justifies a separate classification despite the fact that it is only a transitional phase in the development of drainage. The Whitewater (Wis.) and St. Croix Dalles (Wis.-Minn.) quadrangles show familiar examples of this type.

In regions of complex structure the drainage is usually "complex" in pattern. Sections of such drainage may represent various patterns, depending upon the structural control. For example, on the Guilford (Conn.) quadrangle, there is fairly good rectangular drainage in the west-central part, subparallel in the southern, and dendritic between these two. A structural control furthermore seems to account for the alignment of some of the tributaries in the central and eastern parts. Complexity of pattern is the outstanding characteristic here and determines its classification.

The importance of drainage patterns exceeds the attention thus far devoted to them. They have been fittingly called "the key to a landscape." It is hoped that the present analysis and classification will lead to a better understanding of the various types and thus increase their usefulness to the student of geomorphology. It should, of course, be understood that inferences regarding the geology made from drainage patterns are to be regarded merely as tentative until corroborated by further information.

CORRELATION BY ORDOVICIAN BENTONITE

LAWRENCE WHITCOMB
Lehigh University

ABSTRACT

It is postulated that the Ordovician bentonite beds of Eastern North America were derived from numerous local, rather than one centrally located volcano. Six criteria, which should be considered in any attempt to correlate bentonite beds, are given. In central Pennsylvania a correlation has been established between the bentonite beds over an area which is 70 miles along the strike and 23 miles across the structure. A datum plane has been established throughout the area which cannot vary in age by more than a day or two.

INTRODUCTION

The presence of beds of bentonite in the Ordovician rocks of Eastern North America has now become well known, and numerous papers have been written concerning their occurrence. These papers are found to fall into two main groups: those dealing with the mineralogy and petrology, and those which are confined to the stratigraphic and paleontologic significance of these bentonite beds. In the present paper the problem to be considered is the value of these beds as stratigraphic horizon markers.

The idea of using these bentonite beds as horizon markers is not new, having been mentioned in several papers, and in some cases correlations have been suggested between beds in different areas.[1] It is the purpose of this paper to discuss the methods which may be employed in establishing the identity of a bentonitic bed when found in different areas, and to give one instance in which such a correlation has been worked out in central Pennsylvania over a distance of approximately 75 miles along the strike and 23 miles across the structure.

METHODS EMPLOYED IN CORRELATION

The primary assumption upon which the value of bentonite beds as horizon markers is established is the fact that being the product

[1] C. S. Ross, "Beds of Volcanic Material as Key Horizons," *Bull. Amer. Assoc. Pet. Geol.*, Vol. IX, No. 2 (1925), pp. 341–43; F. W. Sardeson, "Bentonite Seams in Stratigraphic Correlation," *Pan-Amer. Geol.*, Vol. L, No. 2 (1928), pp. 107–16; V. T. Allen, "Ordovician Bentonite in Missouri," *Bull. Geol. Soc. Amer.*, Vol. XLII, No. 1 (1931), pp. 224–25 (Abstract); G. Marshall Kay, "Stratigraphy of the Hounsfield Metabentonite," *Jour. Geol.*, Vol. XXXIX (1931), pp. 361–76.

of a volcanic eruption each bed of ash would be laid down over a large area at the same time. After such an ash fall there is the possibility that parts of the area which were covered might be subjected to erosion or re-working which would destroy the ash layer, but there is no reasonable way in which such a persistent bed could be formed except by the original eruption. Some authorities have suggested that the less pure beds might be "re-worked" material, or eroded ash from adjacent lands. While this might account for some local irregularities or impure beds, it is doubtful if re-working could ever give beds uniform in thickness and character over large areas. It is, therefore, seen that the presence of a uniform and widespread bentonite bed represents an eruption, but that the absence of a bed does not preclude the possibility of there having been such an eruption. Such being the case, if bentonite beds in different localities can be proved to be the product of the same eruption, we have a very accurate horizon marker for close stratigraphic work.

One of the early conceptions in regard to these bentonite beds was that they were all produced by the eruption of one large centrally located volcano. If such were the case, the problem of correlation would be relatively simple, but as bentonite beds have been reported now from the Ordovician formations from Alabama to Ontario in the east, and from beds of the same relative age in Minnesota, Wisconsin, Iowa, and Missouri, the possibility of their being the product of one great volcanic eruption seems to be very slight.

In a recent paper, Kay[1] has correlated the Hounsfield metabentonite over an area extending from Ontario, in the north, to Tennessee, in the south, and westward to the Mississippi Valley. This correlation has been based upon the assumption that the source of the ash was one large volcanic eruption. As evidence in favor of this single center of distribution he states that wherever studied there has been found only one bed of ash, in the beds of Upper Black River age. When, however, it is remembered that there are several beds of bentonite in the Upper Black River of central Pennsylvania and at

[1] G. Marshall Kay, *ibid.*

NOTE.—The manuscript of this paper has been submitted to Kay, who has given helpful criticism.

least six in the overlying Salona formation[1] (Lower Trenton) the question arises as to the validity of this correlation. If all of the bentonite beds were the product of a single widespread fall of ash, some of these other Black River beds also should have been located in other sections. If these beds in Pennsylvania are of limited extent and are not found in other localities, they would strongly suggest local vents. If the Pennsylvania bentonites are the product of some smaller volcano, there is good reason to believe that other beds of bentonite might have been formed in a similar manner, and, therefore, no long-distance correlation can be safely established upon the assumption of a single source for the material.

If these beds are considered to be the product of much more local volcanic disturbances, the problem of their correlation must, of necessity, be undertaken on a local scale at first and gradually extended to other areas. The appearance of beds of bentonite in adjacent areas which interfinger with the local beds is to be expected and should in time lead to a much wider correlation than will be possible until such detailed work is done. One of the greatest difficulties to be overcome is the fact that only a very few of the bentonite beds, as exposed in the field, have been recognized and reported. With only such meager information available, it is very dangerous to draw conclusions for anything but small areas which have been worked intensively.

There are many methods which may be used in attempting to establish the identity of bentonite beds. Each particular area has its own problems, which lead to certain methods being given more weight than might be advisable in some other locality. However, all checks possible should be made, as one method may contradict another. Some of the methods which may be used are given below, with brief statements of their advantages and disadvantages.

1. *The number of beds of bentonite that are found in a formation.*—Although this method may lead to that which looks like a good correlation, it alone is not of sufficient weight to justify its use. Beds may not be found in a section due to the method of exposure, or beds which were actually laid down may have been removed by

[1] R. M. Field, "The Middle Ordovician of Central and South Central Pennsylvania," *Amer. Jour. Sci.*, Vol. XXVIII, 4th ser., No. 288 (1919), pp. 420–21.

erosion, and yet the number found in two or more localities may be the same.

2. *The distance between beds, or the distance that a given bed is found, above some horizon, which is recognizable on other grounds.*—In some cases this method is reasonably accurate, but the same beds may be farther apart in one area than in another due to the more rapid rate of deposition or to the more complete sedimentary record preserved in that region. The value of this method is dependent upon the number of beds being measured, the number of exposures available, and the percentage of exposures which give similar results.

3. *The thickness of the individual beds of bentonite.*—This is a dangerous method to use by itself, as local conditions may very well allow a greater accumulation of ash in one place than in another; also, in areas where the enclosing rocks have been subsequently folded, there may be a great local variation due to squeezing. However, when there is a sequence of thicknesses which are similar over wide areas—as, for example, thick, thin, thick—it is worthy of consideration.

4. *The relationship of bentonite beds to certain well-established faunal zones.*—This is one of the most important methods that can be used, and great care should be taken to try to establish the position of the bed in relation to some such faunal horizon. There are places where there is good evidence that the bottom fauna has been exterminated by such an ash fall, and in such cases there is a distinct change in the fauna at the horizon of the bentonite. When such a case can be proved, there is little doubt about the identity of the two beds under consideration.

5. *The presence, in the rock immediately adjacent to the bentonite bed, of a zone in which the lithology is distinctly different from the normal for the section.*—When such a lithologic change is observed it may be of considerable value. One of the most common variations which is found associated with bentonite beds is the presence of chert in the underlying rock. The origin of this chert or silicified zone is open to debate, but the most probable cause is that the silica was leached from the overlying ash and redeposited in the underlying rocks or unconsolidated sediments.

6. *The possibility of physical or chemical identification of the individual beds.*—There are several investigators whose lines of work include, not only the use of the microscope, but also the X-ray. At present there has been, to the author's knowledge, no report giving physical or chemical tests which can be applied successfully from place to place in the correlation of individual beds.

CORRELATION IN CENTRAL PENNSYLVANIA

As a result of careful stratigraphic work on the Salona formation at the type section Salona, Clinton County, Pennsylvania, in the summers of 1927–29, five beds of bentonite were discovered. Through the work of Bonine and Honess[1] on the bentonites of Pennsylvania, some of these beds are definitely known to be bentonite and, as the others have the same physical characteristics, they are believed to be of the same origin. The location of the beds in the section, and their thicknesses, are given in Table I.

TABLE I

BENTONITE BEDS IN THE SALONA FORMATION AT SALONA, PENNSYLVANIA

Bed	Thickness	Elevation above Base of Section
5	½″	95′ 4″
4	3″	64′ 7″
3	3″	36′ 1″
2	6″	21′ 1″
1	2″	19′ 1″

The two lower beds are by far the most pronounced and obvious ones in the section. They have weathered out more rapidly than the steeply dipping limestone, and leave two distinct depressions in the outcrop.

When these bentonite beds are moist they have a buff color, and on drying they become grayish white. The material weathers out in small, blocky pieces and thin, flat flakes. When placed in water, this substance swells slightly and disintegrates. As soon as it becomes wet, it has a very soapy feeling and is somewhat plastic.

[1] C. A. Bonine and A. P. Honess, "Bentonite in Pennsylvania," *Proc. Penn. Acad. Sci.*, Vol. III (1929), pp. 1–8.

A study of the lithology of the sediments which separate bentonite beds No. 1 and No. 2 reveals that there is a cherty zone directly beneath the upper bentonite. While most of the surrounding rock weathers to a gray color, the 2 or 3 inches immediately under the second bentonite weather to black. The lower limit of this cherty zone is an undulatory surface, and the transition to the normal gray weathering is very sudden, although not a sharply defined, line. The upper surface has a yellowish color and is covered with fossils standing out in relief.

There are two possible conditions under which this silicified zone could have been formed. The first is that it was produced by a slight erosional interval. Under such a condition the presence of the many fossils preserved in relief upon the upper surface would be due to their silicification at or near the surface. Weathered slabs of limestone, in the upper part of the Salona section, on which such silicified fossils stand out in relief, are abundant. Under these conditions the cherty zone would indicate a minor unconformity, and the presence of the bentonite would be a mere matter of chance. However, the presence of the bentonite would be hard to explain if it were deposited before the resubmergence, as it would be destroyed or reworked by the returning waters and would not be uniform in character or thickness. That it happened to be formed just after the resubmergence upon this silicified zone appears highly improbable.

On the other hand, the bentonite might be considered the source of the silica in this cherty zone. Assuming this to be the case, the presence of the fossils on the top surface of the cherty zone would be ascribed to sudden burial, and the chert would be the product of a downward leaching of the silica from the bentonite.

That it is not unusual for bentonite beds to be underlain by such a silicified zone is shown by the fact that the uppermost bed found at Reedsville is resting upon a 1-inch cherty zone. In addition, Dr. Ulrich[1] has stated that in Kentucky some of the bentonite beds are underlain by numerous chert nodules.

If the first hypothesis is accepted, the silicification would have taken place in lithified sediments, and the lower limit of the chert would be much more irregular to account for minor joints or frac-

[1] E. O. Ulrich, personal communication, 1928.

tures, which would allow silicification to proceed to greater depths. Also the distance between the bentonitic beds would vary greatly because of uneven erosion. This is not the case in the sections observed.

It has also been suggested that the silicification is due to the stopping of ascending water containing silica. This explanation seems inadequate, for, under these conditions, the silicification would have been under the first, and not the second, bentonite bed.

There is increasing evidence to show that silicification is an excellent criterion of the physical evidence of a hiatus in limestone. However, in the case of the cherty zone in the Salona, there is probably no such significance, as it is not believed to have been produced by erosion and subsequent silicification but rather by leaching of the bentonite by ground water in the unlithified sediments.

The upper beds of bentonite are not so thick and are not so easily seen as are these two lower ones. Nevertheless, they are decidedly important, as they prove that there was repeated volcanic activity in the source area during Salona time.

In fact, there are now known to be at least ten distinct beds of bentonite in the Middle Ordovician sediments of this area. In addition to this, Williams and Honess[1] have found bentonitic material in residues from the Lowville and Rodman formations when no definite beds were visible. The finding of this material scattered through the formations is suggestive of the conditions that would prevail in unconsolidated sediments if the bentonite were being re-worked or eroded from some adjacent land mass.

Believing that these two lower bentonite beds with the characteristic cherty zone constituted a horizon which could be readily recognized, other exposures of the Salona were visited from time to time. In the fall of 1931, all but one of the different sections which had previously been studied, and also several new localities, were visited by R. R. Rosenkrans, of the department of geology, Pennsylvania State College, and by the writer. As a result of this field work, it is now possible to trace these beds for 75 miles along the strike, from Nippenose Valley to Union Furnace, and across the structure for 23 miles from Bellefonte to Reedsville. Nine different exposures have been studied, and in every instance these basal beds have been seen. In

[1] A. P. Honess, personal communication, 1931.

many of the sections the higher beds have also been discovered. A detailed description of the different sections follows. Figure 1 at the end of this paper gives the sections as measured.

In Nippenose Valley along state highway No. 880, near the gap which leads out to Antes Fort, there is an exposure of the Salona formation in which some of these bentonite beds may be seen. In fact, it was at this locality that Bonine and Honess first noticed the bentonites in Pennsylvania. This exposure is 14 miles along the strike in a northeasterly direction from the section at Salona.

In studying this section, there could be distinguished the lower two beds of bentonite with the same characteristic cherty layer beneath the second bed. The thickness of the beds and the distance between them was very nearly identical with the conditions as found at Salona. The upper surface of the cherty zone had the same types of fossils preserved in relief. They were also in the same stratigraphic position in relation to the zone of *Homalonotus* (*Brongniartella*) *trentonensis*[1] as were the two basal beds at the type section at Salona.

At Bellefonte, Rosenkrans showed the writer the same two lower beds with the characteristic cherty layer. The intervening limestone was 19 inches thick, as at Salona, and the upper 2 or 3 inches were silicified. The top surface of the silicified zone had the same characteristic weathered surface with the same types of fossils standing out in relief. These beds were approximately 15 feet above the base of the Salona formation and below the *Brongniartella trentonensis* zone. Due to the character of the quarry face, we were unable to discover any of the higher beds.

Rosenkrans reports that he has seen the same two beds in the section at Union Furnace and that the lithology of the intervening limestone is identical. The measurements which are given for the Union Furnace section in the tables have been obtained from this source, and the writer is deeply indebted to him, not only for this information, but also for assistance in the field and for much helpful criticism. At Union Furnace the third and fourth beds were also exposed.

At Center Hill, near a small quarry by the roadside, beds 1–4

[1] L. Whitcomb, "New Information on *Homalonotus trentonensis*," *Bull. Geol. Soc. Amer.*, Vol. XLI (1930), p. 348.

were uncovered. The characteristics and stratigraphic location of the two lower beds and the intervening limestone again left no doubt as to their identity.

At Spring Mills, beds 1–4 were again found and measured. As at all previously studied sections, the cherty zone between beds 1 and 2 was persistent, and its top surface had the characteristic weathered surface with the same fossils in relief.

At Coburn the section was badly covered by soil and talus, but the lower three beds were found as in all previous sections. Bed 1 is here found to be only 1 inch thick, whereas in all other sections it had measured from 2 to 3 inches. There is no doubt, however, but that the beds, as found, correspond to beds 1–3 in the other sections. Here again beds 1 and 2 are definitely known to be well below the lower limits of *Brongniartella trentonensis* and not over 15 feet above the base of the section.

At Milroy, in a new road cut, on the northwestern limb of the anticline which forms Kishacoquillas Valley, five beds of bentonite were seen in the Salona. The beds have been overturned in the folding which produced the anticline, but the same characteristics as observed in other sections are to be seen. The two lower beds with the cherty layer are approximately 15 feet above the base of the formation.

At Reedsville, on the southeastern side of Kishacoquillas Valley. there is another good exposure, along the road near the mill dam. Here five beds of bentonite were observed, the lower two being again easily identified as the same two beds seen in all of the other sections.

Near the concrete abutment, at the road junction, is a very pronounced bentonite bed, and working stratigraphically downward four other bentonite beds are to be found. The lower two beds again show the same characteristics as do the lower two at all other sections, the second bed resting upon a cherty zone.

The upper or fifth bed of bentonite found at Reedsville and Milroy is of interest in that it is the best-developed bed in the section and lies above the zone of *Brongniartella trentonensis*. In the section as observed at Salona, all five of the beds that were found were below the top of this fossil zone, which is one of the most characteristic zones of the Salona formation. The presence of this upper bed would

indicate, therefore, that there are at least six beds of bentonite in the Salona formation, instead of the five as seen in the type section. The non-discovery of the sixth bed in the type section is in all probability due to the fact that the upper part of the section is covered by loose soil and all work in that part of the section had to be done in a trench. Under such conditions, it is quite possible that the upper bed was present, but was not observed. There is, of course, the chance that it does not extend that far to the north, but as the other beds are seemingly continuous it is more likely that the bed is present, but was not discovered.

The fifth bed at Salona which was not found in the other sections is only $\frac{1}{2}$ inch thick and was seen in a freshly developed section. Its not having been found in the other sections is explained by the fact that in many cases the upper part of the section was not exposed, and where this upper part was exposed the sections were highly weathered and its identification would be very difficult.

The lower two beds are, therefore, of great importance from the point of view of correlation. In all cases the characteristic cherty zone is present and its upper surface contains the remains of many organisms which were smothered by the ash fall. If these two lower beds of bentonite can be definitely correlated, the top of the cherty zone represents the surface of the accumulated sediments upon which the ash fell and gives a datum plane which cannot vary in age by more than a day or two, and probably by less.

It is believed that these two lower beds may be accurately correlated by means of the following facts (see Figs. 1 and 2). They lie at approximately the same horizon above the base of the formation. They are overlain by other bentonite beds at intervals which are remarkably uniform when one considers the local variations which are possible in any limestone formation. The distance between the two lower beds is remarkably uniform, showing only a slight thinning to the east. They are well below the zone of *Brongniartella trentonensis*. The thicknesses of the two bentonite beds are so nearly identical that any variation could well be produced by local thickening or thinning, caused either by original deposition or the subsequent folding of the enclosing rocks. Bed No. 1 is overlain by 2 or 3 inches of black shale in most of the sections (this shale is bentonitic

in character and may well represent re-worked material washed into the area immediately following the eruption). The upper surface of the intervening limestone displays, throughout, a characteristic zone of silicification. The fossils preserved directly beneath the second bed are always the same and, as there are many complete specimens of the fragile *Cryptolithus tessalatus* standing out in relief, they would

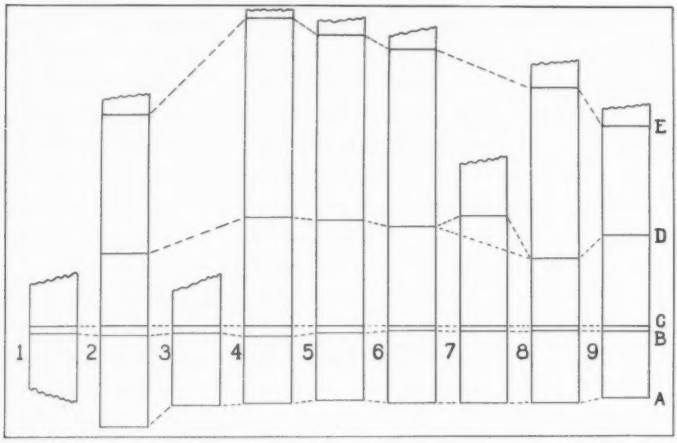

FIG. 1.—Diagram showing the stratigraphic position of the four lower bentonite beds in the Salona formation. Owing to the physical condition of the sections, all four beds were not always found, but beds 1 and 2 were always located.

A is the base of the Salona formation; *B*, *C*, *D*, and *E* are the four bentonite beds.

The localities are as follows: (1) Nippenose Valley, (2) Salona, (3) Bellefonte, (4) Union Furnace, (5) Center Hill, (6) Spring Mills, (7) Coburn, (8) Milroy, (9) Reedsville.

The base of *C*, being the datum plane, which has been established in this paper, has been drawn as a straight line and all other horizons measured from it.

Since the completion of the manuscript of this paper, the writer has received a letter from R. R. Rosenkrans (December 10, 1931) in which he says that the third bed of bentonite (*D* of the diagram) has been found 10 feet 6 inches above the top of the second bentonite bed at Nippenose Valley (column 1 of the diagram).

seem to indicate sudden burial. In no section visited were these characteristic beds found to be missing.

Referring to the six methods, previously given, which may be used in the correlation of bentonite beds, it is seen that as yet No. 6

is of no use and that No. 1 is of doubtful value. The remaining four have all been applied to these lower beds with satisfactory results. It is, therefore, believed that the upper surface of the silicified zone, which directly underlies the second bentonite, represents a datum plane which may be definitely correlated and used in close stratigraphic work.

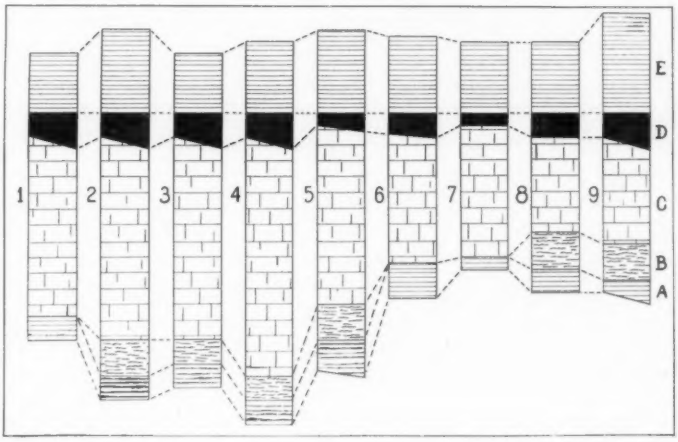

FIG. 2.—Detailed diagram of the first and second bentonite beds (*B* and *C* of Fig. 1) and the intervening limestone, shale, and silicified zone.

Localities are the same as in Fig. 1.

A is the first bentonite bed. *B* is black shale, bentonitic in character. *C* is the limestone which separates bentonite beds 1 and 2. *D* is the silicified zone in the top of the limestone. *E* is the second bentonite bed.

Sections 1–4 are along the strike and 5–9 are across the strike.

Slanting lines indicate variation in thickness within the limits given.

According to information supplied after the completion of the manuscript by R. R. Rosenkrans, the limestone *C* in column 1 is represented as being 6 inches too thick.

The results of this investigation are only a starting point so far as the use of bentonites for correlation in central Pennsylvania is concerned. Additional work is being carried on, by Rosenkrans, to establish the stratigraphic location of other Ordovician bentonite beds in relation to this datum plane below the second Salona bentonite. When this correlation has been established, it will give us much

valuable information regarding the rate of deposition in the different areas of central Pennsylvania. It is hoped that eventually it will be possible to correlate between the bentonite beds of central Pennsylvania and the beds found in some of the surrounding provinces.

In order that the greatest value may be obtained from these Ordovician bentonite beds, it is desirable that more information be published regarding their occurrence and that the information be as complete as possible, giving their relationship to other beds, faunal zones, or any distinguishing characteristics. Many beds of bentonite have undoubtedly been overlooked in the past, but it is hoped that an ever increasing number of localities will be reported in the future. Eventually this information may give clues as to the source or sources of origin of the ash, but at present it seems best to consider that there was more than one vent, and, therefore, that all correlations should be worked out locally, before long-distance attempts are made.[1]

[1] The writer is indebted to Professor R. M. Field of Princeton University, and to Professors A. P. Honess and C. A. Bonine of Pennsylvania State College, who have kindly read the manuscript of this paper and have made suggestions which have been incorporated into the paper. As previously stated, Mr. R. R. Rosenkrans of Pennsylvania State College has supplied measurements for the Union Furnace section and has helped in the field. Mr. B. F. Buie, fellow in geology, Lehigh University, has also spent some time in the field with the writer and has been of assistance as a critical checker of details.

MECHANICS OF FAULTING NEAR SANTA BARBARA, CALIFORNIA

MASON L. HILL
University of Wisconsin

ABSTRACT

Faults near Santa Barbara, trending in two distinct directions, are characterized by steep dips, horizontal displacement parallel to the fault trace, and restricted length. The difference in direction of horizontal relief in different parts of the area establishes two fault systems. Rotational stress acting in N.NW.=S.SE. couples and enduring from late-Pliocene or post-Pliocene time to the present is inferred to be the direct cause of both systems of deformation. The faults are found to differ in essential respects from those previously described. Limitations are placed, (1) on the projection of faults horizontally or at depth, (2) on the use of the physiographic method of fault mapping, and (3) on the reference of seismic epicenters to particular faults.

INTRODUCTION[1]

This paper is a description and structural interpretation of the faults in an area which extends along the Pacific Coast for some 18 miles west of Santa Barbara, California (see Fig. 1).

This area is on the south slope of the Santa Ynez Mountains, which form the westernmost range of the Sierra de Los Angeles.[2] Included within it are local tidal flats, elevated marine terraces (50–150-foot elevations), the Mesa (terraced hills to 600 feet high just southwest of Santa Barbara), and foothills of the Santa Ynez Range. Santa Ynez Peak 5 miles north of the coast is 4,292 feet above the sea.

GEOLOGIC SUMMARY

The geologic column of the Santa Ynez Mountains is comprised of Jurassic (?), Cretaceous, Eocene, Oligocene, Miocene, Pliocene, and Pleistocene rocks. The total thickness, excluding the Jurassic

[1] The work on which this paper is based was begun in 1929 while the writer was engaged in field work for the Shell Company of California. Appreciation is due Dr. T. L. Bailey for suggestions during the field and office work, to Professor W. J. Mead for advice while preparing this paper, and to Professor A. O. Woodford for criticism of the manuscript.

[2] The east-west, anomalously trending coast ranges including also the Santa Susana, San Gabriel, and San Bernardino Mountains (F. L. Ransome, *Problems of American Geology*, Yale University Press, 1913).

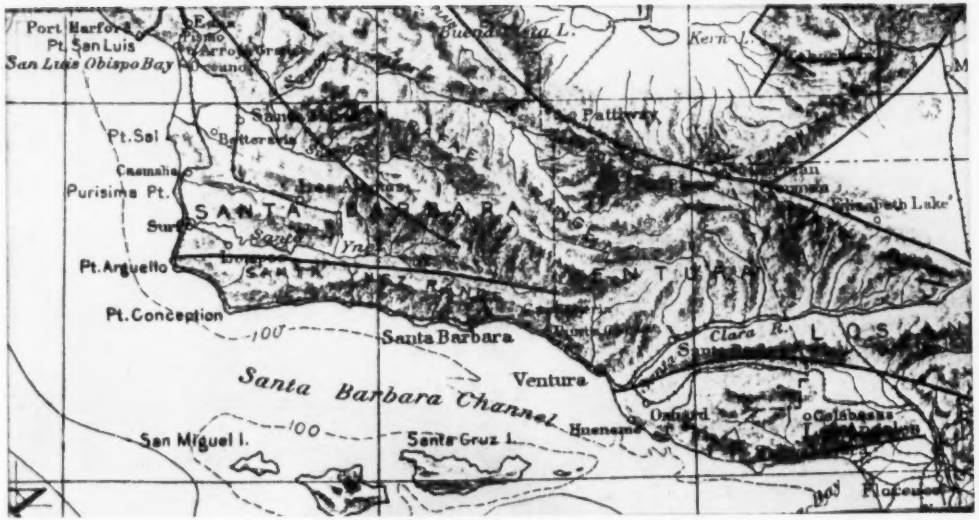

FIG. 1.—Key Map. Adopted from map 1, accompanying the report of the San Francisco Earthquake Commission, 1908.

(?), approaches 20,000 feet of sediments, predominantly marine, and principally of Tertiary age.

The Santa Ynez Range is, at least in part, essentially anticlinal with the axis of the Santa Ynez anticline near the crest of the range. This east-west structure is bounded on the north by the Santa Ynez fault and on the south by the ocean (see Fig. 2).

This paper treats of some of the faulting on the south side of the range. For the general geology of the Santa Ynez region, the reader is referred to Arnold,[1] Arnold and Anderson,[2] Kew,[3] and Nelson.[4]

METHOD OF APPROACH

The area under consideration, which is part of the much-deformed Coast Range region, has responded to deformative forces principally by faulting. The problem, which the writer has attempted to solve, is the determination of the character and direction of stress action which has deformed the rocks of the area. The method of attack on this problem is the application of the fundamental relationship between stress and resulting fracture planes in rocks to the fracture pattern and fault displacements.

The mapping has clearly revealed many of the fault characteristics which are described in the following order: distribution, attitude, displacement, relative importance, and physiographic expression. Then, by analysis of these data, inferences are suggested regarding: the character of deformation, the time of deformation, stress directions involved, local and regional structural relations, and the diastrophic significance. A brief detailed description of each fault is added for completeness, and finally a discussion is given of the relation of this study to previous work in the area and to structural, physiographic, and seismic problems.

The method of approach to the solution of this problem, as out-

[1] R. Arnold, "Geology and Oil of Summerland District," *U.S.G.S. Bull. 321* (1907).

[2] R. Arnold and R. Anderson, "Geology and Oil of Santa Maria District," *U.S.G.S. Bull. 322* (1907).

[3] W. S. W. Kew, "Geology of Santa Maria River District," *Univ. Calif. Publ. Geol. 12* (1919), pp. 1–21.

[4] R. Nelson, "Geology of Upper Santa Ynez River District," *Univ. Calif. Publ. Geol. 15* (1925), pp. 329–92.

lined above, is not original but has been successfully used by Leith,[1] Chamberlin,[2] Ray,[3] and others. Often, this method is not followed and some of the fault characteristics are not considered, either because of their obscurity or because they are not essential to the purpose of the mapping at hand. In such cases, inferences, if drawn, may be erroneous, since all the influencing characteristics are not known. Thus a conclusion regarding the direction of maximum elongation (easiest relief) to stress without knowing the relative components of fault displacement would be poorly grounded. Occasionally inferences are doubtful because of questionable preliminary assumptions. An example of such fallacious reasoning is the attempt to determine the direction of stress involved in a deformation without knowing the orientation of relative relief to stress. Certain assumptions may cause false characteristics to be assigned to structures. Thus, if a fault-block mountain range is erroneously considered the result of tension, the boundary faults may be incorrectly interpreted as of the normal type.[4]

The manner of attack outlined above and applied to the faulting in this study emphasizes the interrelation, or system, of structures. The ultimate value of this group treatment is its bearing on problems of regional structure and diastrophism. This geologic method is essentially inductive, as contrasted with the more deductive methods of astronomical and geophysical reasoning on earth diastrophism.

FAULTING

GENERAL DESCRIPTION

The map (Fig. 3) shows the distribution and relative displacement of the faults. Table I shows the character and classification of the faults.

Distribution.—There are seventeen rather equally spaced faults in the area. The average length is about 3 miles and none appears

[1] C. K. Leith, *Structural Geology*, Henry Holt & Co., 1923.

[2] R. T. Chamberlin, "The Strain Ellipsoid and Appalachian Structure," *Jour. Geol.*, Vol. XXXVI (1928), pp. 85–90.

[3] James C. Ray, "Age and Structure of Vein Systems at Butte, Montana," *Amer. Inst. M. M. E. Tech. Publ. No. 265* (1930).

[4] Mason L. Hill, "Structure of the San Gabriel Mountains North of Los Angeles, Calif.," *Univ. Calif. Publ. Geol. 19* (1930), pp. 137–70.

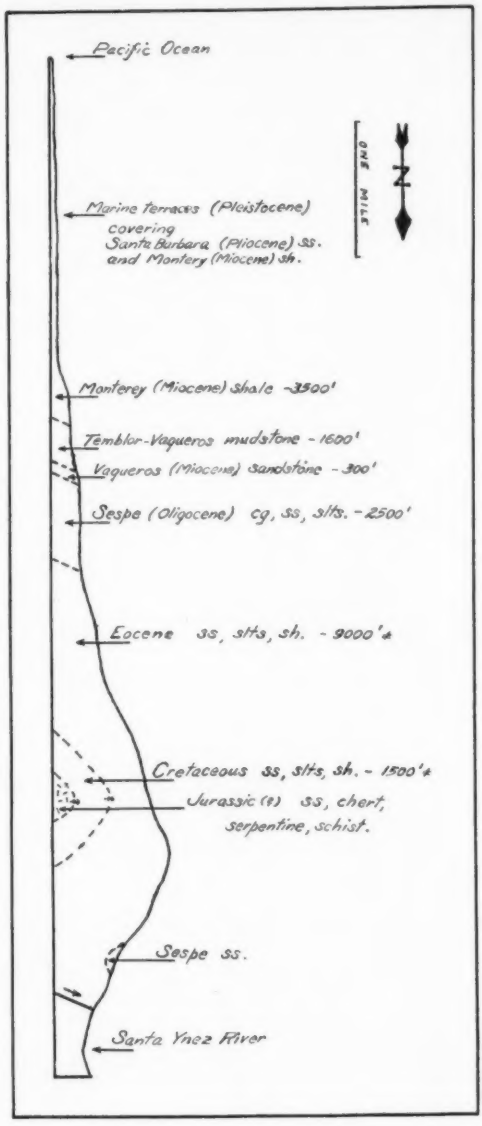
Pacific Ocean
ONE MILE
N
Marine terraces (Pleistocene) covering Santa Barbara (Pliocene) ss. and Monterey (Miocene) sh.
Monterey (Miocene) shale ~3500'
Temblor-Vaqueros mudstone - 1600'
Vaqueros (Miocene) sandstone - 300'
Sespe (Oligocene) cg, ss, slts. - 2500'
Eocene ss, slts, sh. - 9000'±
Cretaceous ss, slts, sh. - 1500'±
Jurassic (?) ss, chert, serpentine, schist.
Sespe ss.
Santa Ynez River

FIG. 2.—Generalized section through the Santa Ynez Range

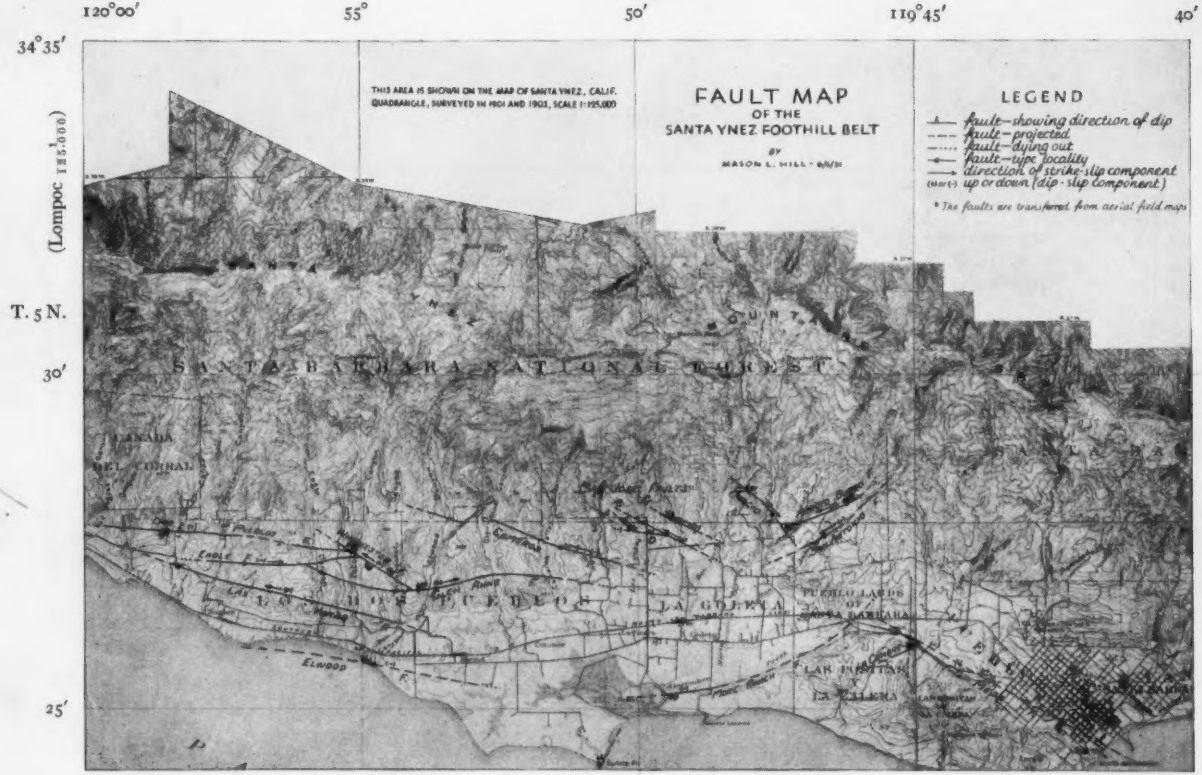
120°00′
55′
50′
119°45′
40′
34°35′
(Lompoc 1:125,000)
T. 5 N.
30′
25′
THIS AREA IS SHOWN ON THE MAP OF SANTA YNEZ, CALIF. QUADRANGLE, SURVEYED IN 1901 AND 1903, SCALE 1:125,000
FAULT MAP
OF THE
SANTA YNEZ FOOTHILL BELT
BY
MASON L. HILL - 6/31
LEGEND
fault—showing direction of dip
fault—projected
fault—dying out
fault—type locality
direction of strike-slip component
(down) up or down (dip-slip component)
The faults are transferred from aerial field maps
SANTA YNEZ
SANTA BARBARA NATIONAL FOREST
GOLETA
EL CERRAL
Eagle Fault
Mesa Fault
Glen Annie Fault
Goleta Fault
Hollister Fault
Storke Fault
Modoc Fault
Elwood Fault
LA GOLETA
PUEBLO LANDS OF SANTA BARBARA
LAS POSITAS
LAS PUENTES
LA CUMBRE
SANTA BARBARA

FIG. 3

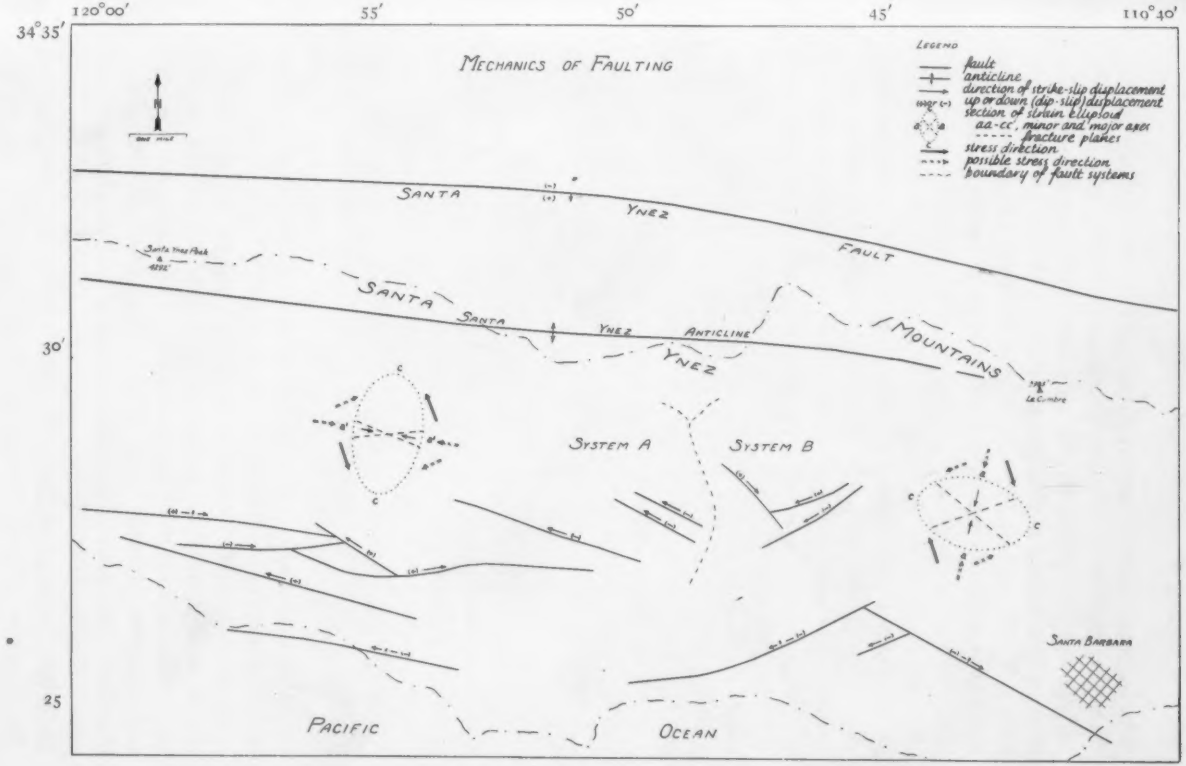
120°00′
55′
50′
45′
119°40′
34°35′
30′
25
MECHANICS OF FAULTING
LEGEND
fault
anticline
direction of strike-slip displacement
up or down (dip-slip) displacement
section of strain ellipsoid
aa-cc', minor and major axes
fracture planes
stress direction
possible stress direction
boundary of fault systems
SANTA YNEZ FAULT
SANTA YNEZ ANTICLINE
SANTA YNEZ MOUNTAINS
SYSTEM A
SYSTEM B
PACIFIC OCEAN
SANTA BARBARA

FIG. 4

to be more than 6 miles long. The faults die out or terminate against each other and are rarely offset by minor faults (Fig. 3).

Attitude.—The faults show nearly straight traces and may be grouped into one set with an approximate E.NE. strike and another with a W.NW. strike. The high dips of the fault planes are either north or south, and even reverse direction along the same fault. No real classification can be derived from their dips except that they are typically steep (see Table I).

TABLE I

FAULT-CLASSIFICATION*

		Strike	Strike-Slip	Dip	Dip-Slip	Length in Miles
System A						
Set 1	Elwood	N. 80 W.(?)	N. side W.(?)	Steep N.	N. side down	(?)
	Las Varas	N. 75 W.	N. side W.	Steep	N. side up	5.5±
	Winchester	N. 57 W.	N. side W.	Steep N.	N. side up	2 ±
	Cameros	N. 72 W.	N. side W.	Steep	N. side up	4 +
	San Jose A	N. 50 W.	N. side W.	Steep	N. side down	1.5+
	San Jose B	N. 63 W.	N. side W.	Steep	N. side down	1.5+
	San Jose C	N. 65 W.	N. side W.	Steep N.	N. side down	1 +
Set 2	Dos Pueblos	N. 85 W.	N. side E.(?)	Steep S.	N. side up	4.5±
	Eagle	N. 88 E.	N. side E.	Steep	N. side down	3 ±
	Glen Anne	E.–W.	N. side E.	Steep	N. side up	5.5±
	San Jose D	N. 85 W.	N. side E.(?)	Steep	N. side down	.5±
System B						
Set 1	Ynacio	N. 45 W.	N. side E.	Steep N.	N. side up	1.5±
	Mesa	N. 78 W.(?)	N. side E.(?)	Steep (?)	N. side down	5 +
Set 2	Arroyo Burro	N. 70 E.	N. side W.	Steep	N. side up	1.5+
	San Antonio	N. 63 E.	N. side W.(?)	Steep	N. side down	2.5+
	More Ranch	N. 70 E.(?)	N. side W.(?)	Steep	N. side down	4 +
	La Cumbre	N. 70 E.	N. side W.	Moderate	N. side up	1 ±

* The basis of classification in this table is fault strike and relative direction of horizontal displacement. It will be noticed that the faults of System A, Set 1, strike approximately W.NW. with the north side displaced relatively westward (left-handed offset) whereas the faults of like trend in System B have the opposite horizontal displacement (right-handed offset).

Displacement.—The apparent displacements are dip-slip, either reverse or normal, types, and strike-slip types. Since the faults are steep and even change in direction of dip, no classification into normal or reverse types is made. That strike-slip components of displacement are important and consistent is inferred from offsets, drag effects, and slickensides in the fault planes. The faults may be classified into two groups on the basis of the relative direction of strike-slip: (1) those with the north side displaced relatively westward,

and (2) those with the north side displaced relatively eastward (see Table I). The displacements (net-slip) probably all have both components of slip but the strike-slip component perhaps usually predominates over the dip-slip. The displacements range from hundreds to tens of hundreds of feet.

Relative importance.—These faults are local, or minor, structures relative to the major structure of the Santa Ynez anticlinal range. They are all of the same order of importance as indicated by their correspondence in length and magnitude of displacement. None of them is directly incidental to another fault or to local folding.

Physiographic expression.—The faulting is apparently not reflected directly in the topography. There are scarps without faults and faults without scarps. Where scarps are accompanied by faults they have fault-line characteristics which depend directly on differential erosion. Scarps are even present on the downthrown blocks (obsequent fault-line scarps).[1] In spite of the recency of faulting, the lack of fault scarps is attributed to rapid erosion and to the subordinance of vertical displacement. Such topographic expression is unfavorable to the physiographic method of fault-mapping.

INFERENCES

Character of deformation.—Horizontal and vertical components of fault displacement indicate a combination of horizontal and vertical relief to stress. However, as has been noted, the horizontal component is commonly predominant and is consistent in direction for any one fault; whereas, the vertical component is occasionally inconsistent in direction on the same fault. Therefore, the direction of horizontal displacement may be of use in this fault classification.

Since the faults may be grouped into two trends, the relative direction of horizontal displacement shows that: for one part of the area the faults of one trend show one direction of displacement while those of the other trend have the opposite displacement, and, furthermore, the faults of one trend in one part of the area have a relative horizontal displacement which is the reverse of that for the same trending faults in the other part of the area (see Table I).

Thus, two fault systems are recognized of which System A, of the western part of the area, comprises two fault trends of opposite hori-

[1] Eliot Blackwelder, "Recognition of Fault Scarps," *Jour. Geol.*, Vol. XXXVI (1928).

zontal displacement; and System B, of the eastern part of the area, has two similar fault trends but of the opposite direction of horizontal displacement with respect to the same trend in System A (see diagrammatic map, Fig. 4).

Now it is possible to attempt to determine the orientation of the relief to stress by analyzing the fault displacements for each system. It is evident from the relative movement of the wedges between the intersecting fault trends that System A shows relative elongation (relief) in a N.NE.-S.SW. direction, whereas System B shows elongation in a W.NW.-E.SE. direction (see orientation of the ellipses, Fig. 4).

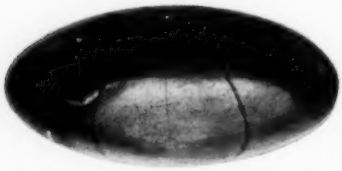

FIG. 5.—The strain ellipsoid

In order to get a three-dimensional concept of the deformation, a strain ellipsoid, as the deformed equivalent of an initial sphere, will be assumed. It has long been known that failure by fracture bears a rather definite relation to the assumed ellipsoid of strain.[1] These fracture, or potential fracture, planes intersect each other at about right-angles along the intermediate axis and are about 45° from the minor and major axes of the ellipsoid (see Fig. 5). The planes tend to be less than 45° from the minor axis of the strain ellipsoid when the rock, in the environment of deformation, is relatively brittle and greater than 45° when relatively plastic.

In System A the angle of the faults to the minor axis of the horizontal ellipse is about 15° (see Fig. 4). If the minor axis of the horizontal ellipse were coincident with the minor axis of the ellipsoid, the faults should be approximately vertical and at 45° to this direction. On the other hand, if this direction were coincident with the intermediate axis of the ellipsoid, the faults should dip about 45° either way and approach parallelism (see Fig. 6). Thus there appears to be a combination of these two extremes of orientation, with the principal section, including the minor and major axes, of the ellipsoid inclined either east or west to give the acute intersection of the fault trends (see Fig. 7).

[1] C. K. Leith, *op. cit.*

In System B the faults are about 60° from the minor axis of the horizontal ellipse (see Fig. 4). This angle may be near the true angle of fracture, because the rocks of this region are relatively plastic and weak under compressional stress. Therefore, the horizontal ellipse is probably near the principal section of the ellipsoid (see Fig. 8).

In both fault systems, then, the maximum elongation is approximately horizontal, but the systems differ in the direction of that elongation. The N.NE.-S.SW. direction of elongation in System A is nearly at right angles to the W.NW.-E.SE. direction of System B and the principal section of the strain ellipsoid is inclined in "A," whereas it is essentially horizontal in "B" (see Fig. 4).

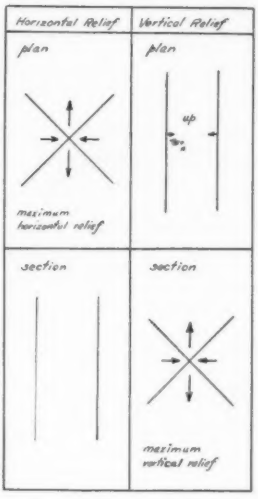

FIG. 6.—Fault patterns for horizontal or vertical relief to deforming stresses.

Time of deformation.—The deformation in this region is considered to have begun near the end of the Pliocene period and to have continued into the present. That profound disturbances in this region began near the close of the Pliocene is indicated by the great unconformity at the base of or within the Pleistocene and the lack of evidence of any considerable pre-Upper Pliocene deformation. The importance of this period of diastrophism has been generally recognized and it is called the Coast Range revolution.[1] The geologic column below the Pleistocene is remarkably conformable down to the great late-Jurassic or post-Jurassic deformation (Sierran revolution) except for an angular discordance of more or less prominence at the base of the Pliocene series. This later deformation perhaps developed rather gentle and local folds without important faulting[2] in this region.

[1] B. L. Clark, "Tectonics of Coast Ranges," *Bull. Geol. Soc. Amer.* 41 (1930), pp. 717–826.

[2] T. L. Bailey, in personal communication, describes a fault exposed in the sea cliff west of Santa Barbara which involves Miocene shales without affecting the overlying Upper Pliocene sands.

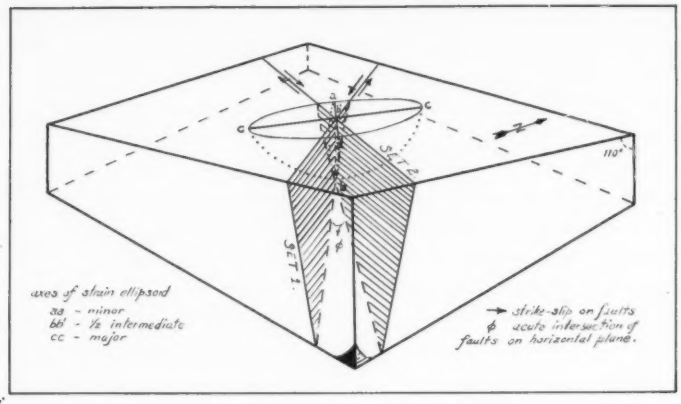

FIG. 7.—System A—Orientation of relief

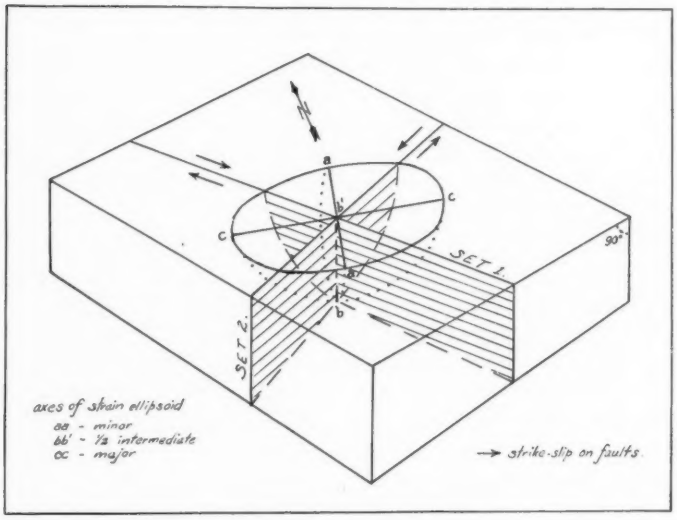

FIG. 8.—System B—Orientation of relief

The continuation of the period of faulting into the present is indicated by faults which involve Pleistocene rocks, by marine terraces, and by the recent seismic activity.[1]

Stress direction.—In both fault systems there are certain limiting possibilities of rotational and non-rotational stress directions.

Non-rotational stress is unlikely for either system, because in this shallow environment, as evidenced by the recency of the faulting and lack of dynamic metamorphism, upward relief would predominate with the development of thrust faults trending normal to the stress. Furthermore, the maximum direction of compression for one system would be nearly normal to that for the other system, and such an extreme and local variation in the direction of the deforming stresses is quite unlikely.

Rotational stress is probable for both systems, since it will, in the shallowest environment, develop maximum relative relief in the horizontal plane on steep intersecting faults. Also, as will be shown, essentially one stress direction may be responsible for both fault systems.

Figure 9, after W. J. Mead,[2] shows the fault pattern developed in paraffin by rotational stress. In this experiment the rotational stress results in N.W.-S.E. horizontal relief by the development of east-west and north-south vertical strike-slip joints and north-east trending tension cracks. The pattern of, and displacement on, these joints simulates the fault characteristics in the Santa Barbara area except for the addition of tension joints. The absence of tension faults may be attributed to the relative plasticity of these rocks in their environment as contrasted with the brittleness of the paraffin. The rapid rate of deformation in the experiment, instead of the leisurely mechanics of nature, is particularly favorable to the development of tension joints.

Now considering the limiting directions of rotational stress in this area it is apparent that couples acting in either E.NE.-W.SW. or N.NW.-S.SE. directions may be responsible for both systems (indicated on Fig. 4). Since the two fault systems, which show the same

[1] Bailey Willis, "The Santa Barbara Earthquake," *Bull. Seis. Soc. Amer.* *15* (1925), pp. 255–78.

[2] "Mechanics of Geologic Structures," *Jour. Geol.*, Vol. XXVIII (1920), pp. 505–28.

type of deformation, are so near each other and essentially contemporaneous, it is likely that one general stress direction may be responsible for both systems. Of the two possibilities the N.NW.-S.SE. couple is chosen because it may be correlated with regional stresses

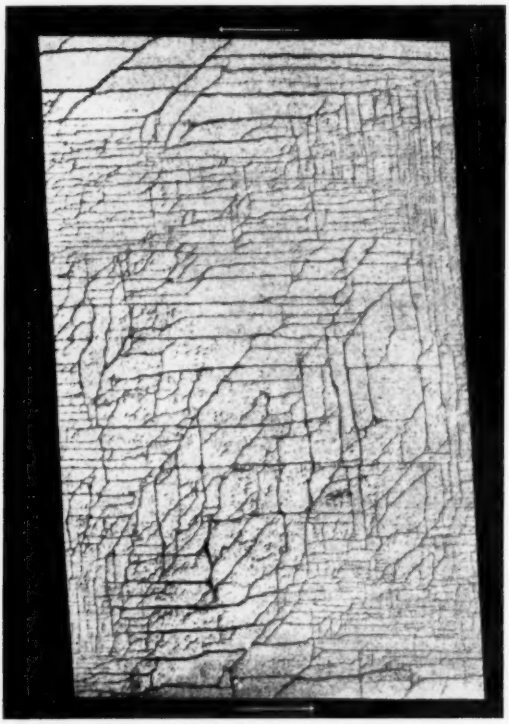

FIG. 9.—Joints and faults produced in paraffin coat on rubber sheet by shearing. The arrows indicate the direction of movement and the shape of the figure shows the amount of distortion. After Mead.

which may be inferred to have developed the regional E.-W. Santa Ynez anticlinal structure (see Fig. 4).

Local and regional structural relations.—The similarity of the fault characteristics, their systematic displacements, their correlation with a common stress direction, and their development during one period

of deformation indicate monogenetic deformation. This means that throughout the time of faulting, perhaps beginning in the Tertiary and surely extending to the present, the environment of deformation has been essentially the same.

The rarity or absence of subsidiary and offsetting faults shows that with continued stress the failure has been easiest on the old fault planes. With horizontal relief this is more likely than with vertical relief because in the latter case the deformation is working directly against gravity. Mead's experiments, cited above, show on continued horizontal relief an increase of the horizontal displacement on the faults or the development of new faults which terminate against the pre-existing ones; whereas, with vertical relief there is a much stronger tendency to form new thrusts after a certain amount of movement on the old. The imbricate structure of the Scottish Highlands is a natural example of this tendency to develop new thrusts.

The striking characteristic of the structure in this region is the local orientation of the relative relief. The faults are rather short and correspondingly shallow, and those in one part of the area are in an entirely different strain system from those in the adjoining area.

The structure in this small area is undoubtedly only incidental to the main structure of the Santa Ynez Range and both are probably subsidiary to a general regional deformation. The parallelism of the east-west trending strata of the Santa Ynez Range with the Santa Ynez fault suggests nearly non-rotational regional stress acting in approximately a north-south direction with maximum relief vertical. This stress direction is very near, and is evidence for, the N.NW.-S.SE. couple which has been inferred for the local structure. It is supposed that the Santa Ynez Mountain structure is itself only incidental to the general structure of the Coast ranges. A discussion of this last problem and particularly the reasons for the anomalous east-west trend of these Coast ranges is beyond the scope of this paper.

Diastrophic significance.—These faults are exemplary of strike-slip displacement, so well shown on the San Andreas rift, but seldom ascribed to other faults in the Coast ranges. The structure emphasizes the local character of relief under presumed regional stress and

the limitation in such circumstances of projecting faults either horizontally or at depth. Furthermore, the structure appears to be the result of rotational deformation instead of non-rotational. These stresses are inferred to be compressive in nature and consistent in direction. This consistency in the direction of the stresses suggests a consistent fundamental cause, either continuous or periodic; whereas, the resulting faulting has been spasmodic, as evidenced by seismic activity. It is impossible at this time to evaluate the significance of these faults, in the interpretation of Coast Range structure or for prevailing theories of diastrophism.

SPECIFIC FAULT DESCRIPTIONS[1]

Elwood fault.—The evidence for the Elwood fault is best shown at the mouth of Bell Canyon where it bounds the oil-producing Elwood anticline on the north. An aerial submarine photo shows truncation of the strata. A well just west of Bell Canyon passes through a fault which dips approximately 85° northward, and since the wells to the south do not pass through important fractures the main fault is considered to have a steep north dip. Both fault walls are of Monterey (Miocene) shale with the north side relatively dropped. The fault apparently dies out within 3 miles to the east and extends under the ocean for an unknown distance to the west.

Its classification into System A, Set 1, is based only on the indefinite trend and is therefore quite conjectural.

Las Varas fault.—The type locality[2] of this fault is taken in Las Varas arroyo a few hundred feet south of the Coast highway. Here, a patch of Vaqueros (Miocene) sandstone lies south of and in steep fault contact with Temblor-Vaqueros mudstone. The fault is traced through the mudstone by brecciation, local deformation, calcite veins, and displacement of marker beds for less than 2 miles N. 75° W. and about 4 miles in the opposite direction. The apparent throw at the type locality is near 850 feet relative elevation of the south side, and the apparent horizontal offset of the projected basal Mon-

[1] See Figure 3 for trend, extent, and location of the type locality of the faults, and Table I for fault classification.

[2] Type localities are selected in order to avoid possible confusion in fault nomenclature (H. J. Buddenhagen and Others, "Type Locality of a Fault," *Bull. Amer. Assoc. Pet. Geol. 14* (1930), pp. 797–98.

terey shale near Bell Canyon is approximately 1,500 feet, the north side having moved relatively westward.

The classification of this fault into System A, Set 1, is based on trend and direction of horizontal displacement.

Winchester fault.—This fault is exposed in a west tributary of Tecolote Canyon, about 3,000 feet S.SW. of the SW. cor. Sec. 34, T. 5 N., R. 29 W. Here Sespe (Oligocene) strata lie on and north of uppermost Vaqueros (Miocene) sandstone. An excavated outcrop shows 8 inches to 2 feet of gouge striking N. 57° W. and dipping 35° N. (the low dip attributed to local creep). To the southeast the fault is within Sespe sandstone and siltstone where one outcrop shows a 65° S. dip and another dips 70° N. The fault terminates to the southeast against the Glenn Anne fault and dies out to the northwest in the Sespe formation. Stratigraphic offset shows apparent upthrow of the north side while drag of strikes and pitch of local folds indicates a westward movement of the north side as well.

Trend and inferred horizontal offset allow classification into System A, Set 1.

Cameros fault.—The type locality is taken on the 366-foot knob just east of Cameros Canyon. At this place south-dipping Vaqueros (Miocene) sandstone is south of and faulted against Temblor-Vaqueros mudstone. Toward the west Sespe (Oligocene) sandstone is south of the mudstone and to the east the mudstone is south of Monterey (Miocene) shale. The fault has a straight trace over the irregular topography and strikes about N. 72° W. The apparent throw near the type locality is approximately 1,600 feet relative elevation of the south side and at the same place the apparent relative horizontal offset of the north side westward is near 13,000 feet. The net slip is undoubtedly some combination of these vertical and horizontal components.

Trend and horizontal displacement place this fault in System A, Set 1.

San Jose A fault.—This fault is well evidenced about 2,500 feet W.SW. of SE. cor. Sec. 32, T. 5 N., R. 28 W., where Vaqueros (Miocene) sandstone is northeast of and dropped down against the Sespe (Oligocene) formation. The fault is steep, trends N. 50° W., and terminates to the SE. against the San Jose D fault. The apparent

throw is about 500 feet and the apparent horizontal offset (if any) is relatively southeast on the southwest side, because the Vaqueros sandstone is not repeated to the NW.

Trend and relative direction of horizontal displacement and analogy to San Jose B and C faults place this fault in System A, Set. 1.

San Jose B fault.—The type locality may be taken 1,800 feet west of the SE. cor. Sec. 32, T. 5 N., R. 28 W. The relationships are analogous to San Jose C fault with apparent throw of 500 feet and apparent horizontal displacement of 1,500 feet. This fault also belongs to System A, Set 1.

San Jose C fault.—The type locality is 1,000 feet E.NE. from SE. cor. Sec. 32, T. 5 N., R. 28 W. Here Sespe (Oligocene) strata are southwest of Temblor-Vaqueros mudstone. The excavation of a pit showed the attitude of the fault plane to be N. 53° W., 72° N., with slickensided grooves dipping 60° NW. along the plane. Mapping showed 1,550 feet apparent horizontal offset of the basal Vaqueros sandstone of the northeast side to the northwest and 775 feet apparent relative elevation of the southwest side. Assuming an average strata attitude of N. 80° E., 50° S., and that the slickensides indicate relative direction of total movement, the dip-slip, strike-slip, and net-slip are calculated to be 710, 400, and 825 feet, respectively.

This fault is definitely classified according to trend and horizontal displacement into System A, Set 1.

Dos Pueblos fault.—The Dos Pueblos fault is best seen about 2,200 feet SW. of SW. cor. Sec. 31, T. 5 N., R. 29 W. Temblor-Vaqueros mudstone is against and south of Sespe strata. The fault trends N. 85° W. and its trace on the topography indicates a steep south (?) dip. The apparent relative elevation of the north side is greater than 400 feet. This fault dies out to the west near Las Yeguas Canyon and abuts against the Winchester fault to the east.

Conjectural classification into System A, Set 2, is made on the basis of fault trend, but direction or amount of horizontal displacement is unknown.

Eagle fault.—The type locality of this fault is taken 4,200 feet south of the SW. cor. Sec. 32, T. 5 N., R. 29 W. Here Vaqueros sandstone is relatively elevated against Temblor-Vaqueros mudstone.

The fault trends N. 88° E. and its trace indicates a steep dip. The apparent throw at the type locality approaches 500 feet, and the apparent relative horizontal displacement of the north side to the east is about 9,000 feet. The fault dies out in the mudstone about 1 mile west of the type locality and terminates against the Winchester fault to the east.

Trend and horizontal displacement allow classification of the Eagle fault in System A, Set 2.

Glen Anne fault.—This fault is clearly exposed 6,000 feet south of the SW. cor. Sec. 35, T. 5 N., R. 29 W. Vaqueros sandstone is relatively dropped with respect to the Sespe (Oligocene) strata on the north. The fault plane strikes N. 85° E. and dips 80° N. with mullion grooves dipping 25° ± westward in the plane. The apparent throw at the type locality is about 1,000 feet. Drag dips, local folds, blocks of Vaqueros sandstone in fault zone, and chatter marks in the mullion structure indicate the north side to have moved, relative to the south side, up and to the east. A block of sandstone was found 1,800 feet east of the same sandstone in place so that the apparent horizontal offset probably exceeds that amount. The 25° ± west-dipping mullion grooves, if they represent the direction of the entire movement, also show that the horizontal component of movement is approximately twice as great as the vertical. The apparent reversal of throw east of Cameros Valley may be best explained by a combination of folding and horizontal displacement.

The trend and direction of horizontal displacement clearly place this fault in System A, Set 2.

San Jose D fault.—This fault trends N. 85° W. between the San Jose A and B faults. The south side is relatively elevated to repeat the Sespe-Vaqueros contact by an apparent throw of about 700 feet. Strike-slip component is unknown.

Classification into System A, Set 2, is based on fault trend.

Ynacio fault.—The type locality is taken 800 feet north of the SW. cor. Sec. 35, T. 5 N., R 28 W., where Vaqueros sandstone is southwest of Sespe strata. The fault strikes N. 45° W., and its trace indicates a steep dip. The apparent relative elevation of the northeast side here is about 800 feet, and the apparent relative horizontal offset of the northeast side to the southeast is about 1,500 feet.

These data allow classification of the Ynacio fault into System B, Set 1.

Mesa fault.—This fault is not exposed, but the northeast-facing scarp of the Mesa, just southwest of Santa Barbara, which exposes Sespe and Pliocene strata, is inferred to be the result of faulting.

The trend of this fault suggests classification is System B, Set 1.

Arroyo Burro fault.—The type locality of this fault is 2,400 feet northeast of the SW. cor. Sec. 36, T. 5 N., R. 28 W. where Sespe rocks are against and north of Temblor-Vaqueros mudstone. The fault plane is vertical and strikes N. 75° E. with slickensides dipping 25° E. in the plane. The apparent relative throw is down on the south side, and apparent relative horizontal offset of the northwest side to the southwest is about 1,300 feet. Drag folds also indicate the same direction of displacement. Assuming these data characterize the total displacement, the oblique slip, strike-slip, and dip-slip are calculated as 1,450, 1,300, and 600 feet, respectively.

The trend and horizontal displacement place this fault in System B, Set 2.

San Antonio fault.—This fault is evidenced 1,200 feet S.SW. of the SW. cor. Sec. 36, T. 5 N., R. 28 W. Temblor-Vaqueros mudstone is north of Sespe strata. The throw probably exceeds 500 feet. No direct conclusion on the direction of horizontal displacement can be made because the Sespe-Vaqueros contact projected from the east might correspond to its outcrop to the northeast, or its concealed position under the Quaternary conglomerate to the southwest, on the northwest side of the fault.

Fault trend suggests classification into System B, Set 2.

More Ranch fault.—This fault is marked by the scarp along the northwest side of the Mesa, south of Goleta. Wells drilled on both sides of the scarp show 1,500 feet apparent upthrow of basal Miocene sandstone south of the fault. A steep dip of the fault plane is indicated.

The trend suggests classification into System B, Set 2.

La Cumbre fault.—The type locality is 5,300 feet north of longitude 119°45′ and latitude 34°25′. The excavation of a pit showed Sespe strata north of Pliocene sandstone with the fault plane striking N.

70° E., dipping 50° N., and slickensides dipping 50° E. These data indicate an oblique movement of the north side relatively up and westward.

The trend and horizontal component of movement allow the fault to be classified into System B, Set 2.

CONCLUSIONS

DEPARTURE FROM PREVIOUS INTERPRETATIONS

The fault map of California[1] shows a few ascertained and conjectural faults in this region. Willis[2] gives fault maps and a cross-section for this area in his paper on the Santa Barbara earthquake. His faults include the South Santa Ynez, Naples, Mesa, and two unnamed ones. The Naples fault is considered non-existent by the writer, and the scarp is definitely referred, in places, to differential erosion due to a siliceous member in the Vaqueros-Temblor mudstone. The South Santa Ynez fault of Willis is here mapped crossing Cameros Canyon but with a different trend and shorter length (Cameros fault of this paper). The Mesa fault was mapped by Willis as arcuate and with a branch extending to the South Santa Ynez fault. Here it is mapped along the northeast side of the Mesa but dying out, or terminating against another fault, before reaching the Cameros (South Santa Ynez) fault, while a separate fault is evidenced along the northwest side of the Mesa. Fourteen other faults of the same order of importance as these, but not previously described in the literature, are mapped in this work. Willis' cross-section shows a general south dip for the faults with flattening to a gentle southerly dip at depth, and reaching a depth of 15–40 miles. The faults are typically steep where exposed and are here considered to continue so at depth. They are short in surface trace and perhaps of less depth than length. Predominance of vertical displacement seems to be inferred by Willis, whereas this work emphasizes the importance of horizontal displacement.

Thus the author's map and interpretations differ notably from those of previous workers in the area.

[1] Bailey Willis and H. O. Wood, *Fault Map of California, Seis. Soc. Amer.*, 1922.

[2] Bailey Willis, *op. cit.*, pp. 255–78.

STRUCTURAL, PHYSIOGRAPHIC, AND SEISMIC APPLICATIONS

The local character of the relief indicates that the faults in this area may not be conjecturally extended far and that faults of one system may not be projected into another system. The shallowness of the faults, as inferred from their short length, suggests that they should not be projected to depths exceeding 6 miles.

The physiographic method is not adequate for fault-mapping in this region, in spite of the recency of deformation, because of the rapid erosion of rocks of differential resistance and the relative unimportance of the vertical component of the displacements.

The presence of many equally important and potentially active faults makes the reference of a certain seismic disturbance to one particular fault quite difficult. At the time of the 1925 earthquake there were no short-period seismic stations closer than Pasadena, California, so the location of the epicenter, or epicenters, was not very satisfactory.[1] Possibly even with the best instrumental data the epicenters and foci could not be located closely enough to be attributed to particular faults in this area.

EVALUATION OF CONCLUSIONS

The value of the conclusions, summarized in the abstract, depends on the completeness of the data and the logical sequence of inferences.

The position of the Mesa fault is not definitely ascertained. The trends of the Mesa, More Ranch, and Elwood faults are not absolutely certain. The relative strike-slips of the Mesa, More Ranch, Elwood, San Jose D, Dos Pueblos, and San Antonio faults are not absolutely established. However, the data on the other eleven faults are rather complete and are thought to justify the inferences.

The primary assumption underlying this study is the acceptance of a definite relation of deformation (strain) to the deforming forces (stress).

[1] H. O. Wood, personal communication.

MAP OF THE SCHOOLEY (KITTATINNY) PENEPLAIN

KARL VER STEEG
College of Wooster

ABSTRACT

This paper presents a contour map of the restored upper peneplain represented by the even crest-lines of the folded Appalachians in eastern Pennsylvania.

The writer has endeavored to map a portion of a (warped) peneplain, largely removed by erosion, and it is therefore impossible to restore all the features of the original surface. The map was constructed on the assumption that the tops of the ridges present nearly their original surface outline. Walking along the Appalachian ridges, one observes that in most cases their crests are broadly rounded or nearly flat topped, in many instances quite wide and with low monadnocks on them.

The Susquehanna River is shown on the map occupying a wide valley-like warp in the restored surface. It is probable that this depression represents the valley of the Susquehanna River developed during the Schooley (Kittatinny) cycle. To the southeast lies the Broad Mountain arch, merging into the Pocono Plateau to the northwest. On this extensive surface were numerous monadnocks, only a few of which are shown. With few exceptions, points marking the apices of anticlines and synclines stand well above the general level of the peneplain, owing to slower erosion here as a result of greater thickness of the resistant beds. At few places is the slope of the restored surface greater than 5°; how much of this is due to warping cannot be determined. In addition to the monadnocks mentioned there were doubtless low, linear ridges, crossed by streams which occupied broad, shallow water gaps, the sides of which sloped at very gentle angles, in most cases less than 5°. The gaps which were deepest were those occupied by the large streams such as the Susquehanna, Swatara, Delaware, Lehigh, and Schuylkill rivers. There were also many smaller streams which crossed the ridges, as indi-

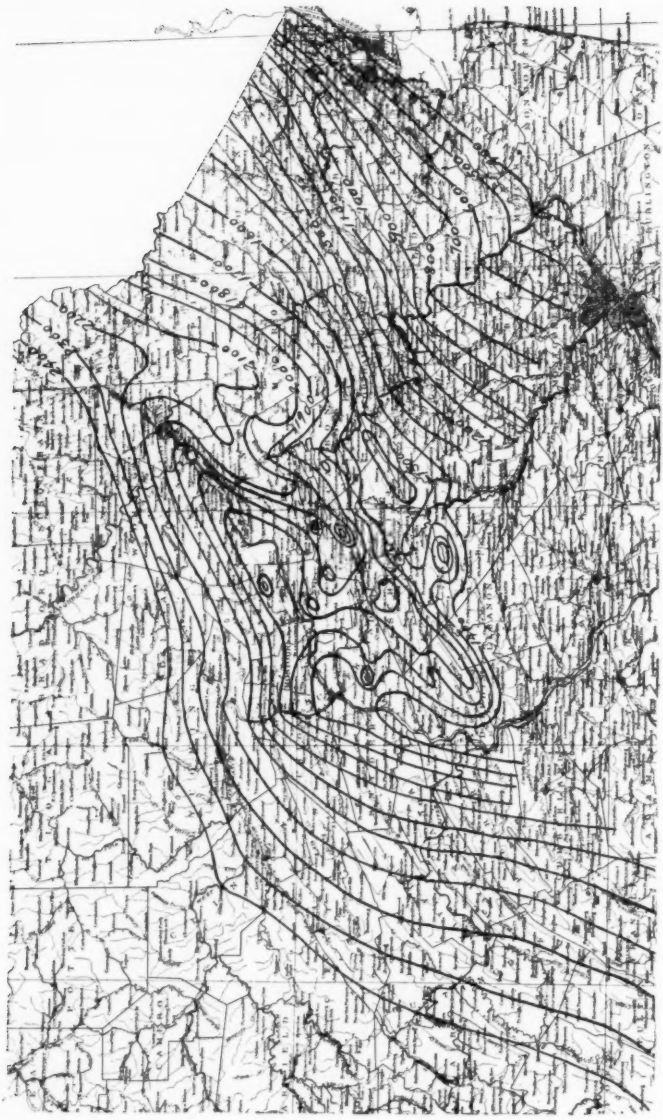

FIG. 1

cated by numerous wind gaps and water gaps which persisted into the post-Schooley (Kittatinny) cycle. There may have been some shallow wind gaps produced during the Schooley (Kittatinny) cycle, not completely removed by erosion, and which now occur at the highest elevations on the ridges. Most of the larger wind gaps and water gaps show wide, shallow sags on the ridge crests, below which the streams have cut their gaps. A general idea can be gained as to the size of the streams on the Schooley (Kittatinny) surface by the breadth and depth of these valleys.

STUDIES FOR STUDENTS

THE GEOLOGICAL HISTORY OF THE SOUTHWESTERN PLAINS OF CANADA[1]

M. Y. WILLIAMS
University of British Columbia

INTRODUCTION

The geological history of the Great Plains is intimately connected with that of the Western Cordillera, and in a large way, in fact, with that of the whole continent of North America. For present purposes, however, the records contained in the sediments, structures, fossils, and land forms of the southwestern plains of Canada will be given special prominence, and from their interpretation, the outstanding events leading up to present conditions will be described.

The background of this history is the late Paleozoic, since Mississippian, and possibly even Devonian limestone, is penetrated by the deep wells sunk for oil and gas. The early Mesozoic too and more than half of the Cretaceous is known within the area only from records of deep well borings. The Montana division of the Cretaceous, however, and the disputed, transitional formations of Upper Cretaceous or early Eocene age (Laramie of Dawson) are exceptionally well represented. The latter occur in three somewhat distinct areas, and correlation is consequently difficult. Early Oligocene continental conditions and life are exceptionally well illustrated in the conglomerates of the Cypress Hills; and subsequent uplift and erosion, representing three cycles at least, are well recorded in physiographic fea-

[1] This paper is based, in general, upon information gathered by the author and his associates during the preparation of the *Calgary Map Sheet* and *Memoir 163* of the Geological Survey of Canada. It is more particularly based, however, on the author's own work within the area extending north 48 miles from the 49th parallel and eastward from the disturbed belt of western Alberta to the 109th meridian, or an average distance of 210 miles. Credit is due to Mr. E. J. Whittaker and Drs. W. S. Dyer and P. S. Warren for information gathered by them in the field. The paper is presented with the permission of Dr. W. H. Collins, Director of the Geological Survey of Canada.

GENERAL TABLE OF CORRELATION
Period | Rhizomys | Central | Southern | Southwestern | Northwest | Cascade

GENERAL TABLE OF CORRELATION

Era	Period, etc.	Blairmore Alberta	Central Alberta	Southern Plains of Alberta	Southwestern Saskatchewan	Manitoba	Northwest Montana	Central and East Montana	Wyoming
	Oligocene				Cypress Formation				White River Formation
Ceno-zoic	Eocene				*Disconformity*			Wasatch / Sentinel Butte	Wasatch / Clark Fork
			Paskapoo	Porcupine Hills			Willow Creek		
			Disconformity	Willow Creek					
Meso-zoic	Upper Cretaceous		Edmonton	St. Mary River	Ravenscrag		St. Mary River	Fort Union	Fort Union
					White Mud			Lance (Hell Creek)	Lance
					Estevan				
			Fox Hills	Fox Hills	Fox Hills		Horsethief	Fox Hills	Fox Hills
		Allison	Bearpaw	Bearpaw	Bearpaw	Odanah	Bearpaw	Bearpaw	Bearpaw
			Belly River	Belly River	Belly River	Millwood	Two Medicine	Judith River	Pierre
			Lea Park	Pakowki	Pakowki			Clagett	
			Absent	Milk River	Milk River		Virgelle	Eagle / Upper Eagle Virgelle	
		Colorado	Colorado	Colorado	Colorado	Niobrara	Colorado	Colorado	Niobrara
						Benton			Benton
	Lower Cretaceous	Blairmore Kootenay	Pre-Colorado	Blairmore Kootenay	Kootenay?	"Dakota"	Kootenay	Kootenay	Cloverly
	Upper Jurassic	Fernie	Upper Jurassic	Upper Jurassic	Upper Jurassic		Ellis	Ellis	Sunburst
		Disconformity	*Disconformity*	*Disconformity*	*Disconformity*	*Disconformity*	*Disconformity*		*Disconformity*
Paleo-zoic	Generally Mississippian	Paleozoic	Paleozoic	Madison (Lower Mississippian)	Paleozoic (Madison?)	Paleozoic	Madison (Lower Mississippian)	?	Paleozoic

tures. The passing stages of the ice age are mapped by the abandoned river channels, and recent uplift is depicted in the incised channels of the present rejuvenated drainage.

LATE PALEOZOIC

Marine Paleozoic sediments are found in the Rocky Mountains and in deep wells, the youngest being Carboniferous in age. In the Flathead Valley, Mackenzie[1] found limestone of early Pennsylvanian age, and determined the Rocky Mountain quartzite of the area as probably Permian, but in the Sweet Grass Hills, and underlying the southern plains, the youngest Paleozoic beds appear to be Mississippian. These are distinguished by many brachiopods of the genus *Productus*. It is inferred that Paleozoic seaways periodically occupied the Rocky Mountain geosyncline and the area now forming the adjoining plains until at least Pennsylvanian time. An upwarping occurred, probably in late Permian time (cf. Mackenzie) with resultant continental erosion, the emergent interval lasting into the Mesozoic. This uplift of the Great Plains was approximately contemporaneous with the Appalachian revolution of Eastern America, and the erosion, with the Permian and Triassic erosion of the Appalachian Mountains. A land surface was finally developed upon early Pennsylvanian formations in southeastern British Columbia, on early Permian Rocky Mountain quartzite farther north, upon Mississippian dolomite over the area bordering the Rocky Mountains on the east, upon Middle Devonian limestone in the belt of country west of the Great Lakes of Manitoba, and on Middle and Upper Devonian formations in the Mackenzie River basin. In view of the greater thicknesses of the formations in the Rocky Mountain geosyncline compared with those farther east, the beveled erosion surface may not indicate differential uplift, but may in fact be the normal result of nearly uniform regional uplift. The great erosion surface at the top of the Paleozoic is the most important disconformity over the vast region concerned and demands consideration by all geologists.

MESOZOIC HISTORY

Triassic time appears to be represented in the Southern Rockies, according to Mackenzie, by a white sandstone possessing properties

[1] J. D. Mackenzie, *Trans. Roy. Soc. Can.*, Vol. XVI, Ser. 3, p. 100.

of both aeolian and aqueous deposits; and Warren[1] assigns the Spray River formation of Banff to the Lower Triassic. Over the plains, however, erosion appears to have been in full force during Triassic time. By early Middle Jurassic time, a broad trough had admitted the sea into the Rocky Mountain region, where the Fernie shales of early Middle Jurassic[2] age at Sheep River and of early Upper Jurassic age in the Blairmore area were deposited. By Upper Jurassic time, this sea had spread eastward beyond Moosejaw, and in it were deposited cherty limestones, shales, and sandstones (Ellis formation) containing marine Upper Jurassic *Gryphaeas* and other fossils. The Ellis formation is rarely over 300 feet thick and appears to be composed of the weathered products of the post-Paleozoic land surface.

It is in the lower beds of the Ellis or near the top of the Madison that most of the oil of Montana occurs. A well drilled at Moosejaw penetrated the Jurassic, which is not known farther east.

The tremendous grano-diorite invasions of the Coast Range and Kootenay batholiths during late Jurassic and somewhat later time were accompanied by mountain building in the west and by uplift as far east as the Purcell Range of today. As a result of erosion in these highlands, the fresh-water Kootenay gravels, sands, and peat beds were deposited to great depths in the Rocky Mountain geosyncline, while finer sands and muds were being washed eastward into the shallow bordering sea. Kootenay time was characterized by rapid river sedimentation, accompanied by vast swamp areas on and between the river deltas. In the swamps, forests of ferns, cycads, and conifers flourished and built up beneath their roots tremendous beds of peat, which are now represented by an estimated aggregate of 200 feet of coal.

Increasing uplift in the west rejuvenated erosion which set free huge quantities of gravels to fill up the swamps and to build up the continental Blairmore formation, which was deposited during the emergent period of transition between Lower and Upper Cretaceous time. This is the "Intermontane Disturbance" of Schuchert. The Blairmore sediments were highly oxidized, due probably to deep weathering at their source, and they appear to be represented in the well borings of the plains by red and green shales which are generally

[1] P. S. Warren, "Banff Area, Alberta," *Geol. Surv. Can. Memoir 153*, p. 41.

[2] F. H. McLearn, *Roy. Soc. Can., Proc. and Trans.*, Vol. XXI, Ser. 3 (1927), p. 68.

accepted by oil geologists as marking the top of the Kootenay formation.

The widespread distribution of the thin, but persistent, colored shales, is indicative of a period of active chemical as well as mechanical weathering in the area of the Jurassic uplift, and more particularly in the area west of the Rocky Mountains affected by the intermontane uplift. As will be seen from this argument, the "Kootenay formation" of the oil and gas fields should more properly be called the "Blairmore-Kootenay."

The greatest submergence of Upper Cretaceous time followed the deposition of the Blairmore sands and gravels. A shallow sea occupied the Rocky Mountain geosyncline and the vast area to the east, possibly lapping over onto the pre-Cambrian rocks of the Canadian shield: from the 49th parallel, its waters probably extended without interruption into the Arctic Ocean. This Colorado epoch was a time of world-flooding, and Schuchert estimates that at least 40 per cent of North America was submerged. The uniformly shallow nature of this sea is remarkable, as fine, black muds, with thin beds of sand and rare limestone lenses, make up the monotonous series of sediments throughout their extent. Such widespread, even distribution of nearly uniform sediments must be ascribed, it seems, to marine currents. Only small amounts of sediments could be derived from the low pre-Cambrian area to the east, and the mountains and plateaus to the west lay at least 800 miles from the Colorado deposits of central Manitoba. The Rocky Mountain and Alberta geosynclines still continued to subside, for although the sediments here deposited do not vary materially in kind from those farther east, their thickness is much greater, being 2,000 feet in the foothills, nearly 2,000 feet at Coutts, and only 175 feet in Manitoba (Dowling).

The life of the Colorado Sea is represented in drill cores by linguloid brachiopods, pectens, prismatic sections of *Inoceramus* shells, small gastropods, fragments of *Baculites*, and fish scales.

Montana time was ushered in by a gentle withdrawal of the sea in Alberta and western Saskatchewan, and along the retreating shoreline the Milk River sands (Upper Eagle and Virgelle of Montana) were deposited. Thin streaks of coal and silicified wood are the most common evidence of life and prove the existence of con-

siderable forests, probably including both conifer and deciduous trees.

After a comparatively brief interval recorded in some 200–250 feet of sandstone, the Pierre Sea advanced from the east, depositing sands and impure shales as far west as the foothills and even into the Moose Mountain area. The sea was very shallow, and the muddy waters were unfavorable for life judging by the scarcity of fossils found in the sediments. Those occurring include *Baculites compressus* and a few pelecypods and gastropods, all of Lower Pierre character. For some peculiar reason, a very thin bed of fine argillite or black chert pebbles was laid down when this sea advanced, and again as it retreated. Possibly the cherty limestone of Carboniferous age was being eroded in the west. The Lower Pierre sediments make up the Pakowki shale of the south, the Lea Park shale of the north, and the Claggett shale of Dakota and Montana.

With the retreat of the Lower Pierre strand line to eastern Saskatchewan, vast areas remained near sea level, receiving large quantities of sand and mud brought down by the rivers from the west. In the swamps, luxuriant forests grew, building up beneath the roots of successive generations great masses of peat. In ponds and river channels fresh-water gastropods and unios flourished, while just off the ever changing river mouths oysters multiplied, forming strata 3–4 feet thick and of wide extent. Sands, silts, muds, shells, and peat were the sediments which built up the Belly River formation, which contains more brackish water strata in the east and is thicker and more sandy in the west. In the south, the Belly River may be divided into the Lower-Foremost and the Upper-Pale beds divisions; but in the north there are recognized four subdivisions, these being in ascending order: the Ribstone Creek sandstone, the Grizzly Bear shale (representing a distinct marine invasion), the Birch Lake sandstone, and the Pale and Variegated beds. As these sediments were deposited over a vast area, by numerous streams issuing from the western highlands, conditions of sedimentation varied much, and sediments of various kinds resulted.

Vast swamps existed along the rivers, back of the levees, and bordering the great flood plains. In these, peat deposits accumulated. Along the shores of the rivers and swamps, multitudes of

dinosaurs from a few feet to 45 feet in length cropped the succulent herbage or searched for prey, while crocodiles and turtles, amphibians, and primitive mammals played minor rôles. Fishes of several kinds, including lung fish, sturgeon, and gar pike, lived in the rivers and lakes.

The Red Deer Valley of Alberta occupies an area which swarmed with life during Belly River times, as shown by the numerous fossil dinosaurs and other vertebrates contained in the Belly River rocks of this region. Elsewhere, where conditions of preservation were not so good, scattered bones and teeth represent a widespread reptile distribution. Near Lucky Strike, in southern Alberta, twenty-seven different species of reptiles and fishes are represented by bones found in a few hours collecting from a very small area, and in about 2 feet of beds of the Foremost division of the Belly River formation. There were also unios and other fresh-water invertebrates in associated beds.

The fresh-water beds of the Belly River formation contain many gastropods and pelecypods, and the brackish water Foremost beds contain oysters and corbulas in great numbers, along with other molluscs frequenting river estuaries.

The last marine submergence (Upper Pierre) was so great as to remind of the Colorado Sea. The Pierre Sea returned from the southeast depositing the Bearpaw and equivalent muds over southwestern Manitoba, the southern half of Saskatchewan, and the southern two-thirds of Alberta. In even distribution and uniformity, the Upper Pierre muds compare closely with those of the Colorado Sea.

Pelecypods were numerous, especially during the earlier part of the invasion, *Arctica ovata* being the largest representative. Ammonites were rather widely distributed throughout the epoch and *Placenticeras* reached large proportions. *Scaphites* and *Baculites* were fairly common genera.

The water in the Upper Pierre Sea was probably abnormally saline, as the Bearpaw shales contain large amounts of sulphates, selenite crystals forming extensively on the weathering surfaces.

The rhythmic earth movements, which resulted in alternating deposits of fresh-water and marine origin throughout previous Cretaceous time, now became decidedly positive, and with minor oscilla-

tions the plains finally rose above sea level. Gentle warping is indicated in southeastern Alberta, by sandstone dike intrusions, which were followed by a short period of erosion, and then by oscillatory conditions during which the brackish to marine Fox Hills sandstone and shale were spread over southern Alberta and southwestern Saskatchewan. Sharks, and Pierre pelecypods and ammonites made their last stand over vast areas of shallow seaways, their survivors retiring reluctantly to the permanent oceans, where with changing conditions the ammonites were soon exterminated.

The age of the intrusion of the sandstone dikes is definitely fixed as post-Bearpaw and pre-Fox Hills, and as their intrusion coincided with the commencement of the final positive movement of the Great Plains it may be considered as the initial stage of the Laramide revolution. Such warping as occurred left only minor indications in the Fox Hills formation, which is reasonably uniform over its extent, having, as might be expected, more shale in the east than in the west. About the Cypress Hills, however, the sands are more yellow and friable than in the west, and shale members are of considerable thickness. The sea lingered longer here than farther west, and the formation is twice as thick.

With the withdrawal of the Fox Hills–Pierre Sea, shallow-water marine sediments gave place without discordance to continental fresh-water sediments and peat deposits. Meandering rivers built up great flood plains, on which ox-bow and overflow lakes and heavily forested swamps were ubiquitous features. Unios and fresh-water snails lived in the shallow waters and deciduous trees of Tertiary type made up the forest growth.

In Lance time, following the withdrawal of the shallow Fox Hills Sea, 1,600 feet of fresh-water sands and silts were deposited in the Alberta geosyncline which was growing deeper with the upwarping of the Rocky Mountain region. Farther west, in the area now known as the disturbed belt, Stewart reports 2,500 feet of these sediments. With the erosion of the rising land to the west, the sands gave place to highly oxidized muds, and the St. Mary sediments pass upward through a zone of transition into the red and variegated sediments of the Willow Creek formation. The few Willow Creek fossils known suggest post-Fort Union time, the correlation being provisionally

with the Clark Fork beds of Wyoming or the Sentinel Butte beds of southeastern Montana. As the sedimentation in the southwest was apparently continuous, Fort Union time may be represented by the transitional zone, including some of the beds above and below it. In other words, the southwestern Alberta trough appears to have received sediments practically continuously throughout Lance, Fort Union, and Clark Fork time. In the region north of Calgary, the Edmonton formation forms the northern extension of the lower part of the St. Mary River formation, the upper beds being eroded away due to differential uplift. Beginning with late Willow Creek time, as a result of renewed uplift in the west, sands transported from the highlands were deposited in the north as the Paskapoo formation, while the upper Willow Creek shales and the Porcupine sands were being laid down in the southwest.

During Lance time in the Cypress Hills and the southwestern Saskatchewan region, the Estevan sands, silts, and lignites were deposited on stream flood plains. The sediments of this eastern region are more weathered and less consolidated than Lance sediments in the west. Such conditions show even in the Fox Hills sandstones. In later Lance time, the white muds and sands of the Whitemud formation were deposited, representing the transported products of deeply weathered feldspathic rocks. In order to account for the refractory characters of these deposits, and for their alleged greater purity toward the east, Davis[1] postulates an uplift in the east, and a consequent drainage from the pre-Cambrian old land of northern Manitoba and Saskatchewan. Such conditions would require a reversal of the long-established drainage from the west, clearly operative at least until Fox Hills time and proved beyond doubt for early Oligocene time. Such reversals of drainage, to account for a 25-foot formation, seem unnecessary, and contrary to experience. The yellow, highly weathered character of the Fox Hills and Estevan beds, as well as the highly refractory character of the Whitemud beds, need, however, some satisfactory explanation.

There is a possible explanation for the phenomena described. At the close of Bearpaw time, an upwarping in the Cypress Hills region

[1] N. B. Davis, "Rept. on the Clay Resources of Southern Saskatchewan, Mines Branch," *Dept. of Mines, Can.* (1918).

was accompanied by the intrusion of sandstone dikes and similar bodies. The age of the igneous intrusions of the Sweet Grass Hills is generally stated as being early Tertiary, but the exact age is not known.[1] Is it not possible that igneous activity and uplift foretold by sand intrusions began at the close of Bearpaw time and ceased in early Lance time? Such activity in the Sweet Grass Hills would most naturally deflect toward the north the course of the eastward-flowing rivers, and would add a new source of detrital material for the sediments of the Cypress Hills–Wood Mountain region. The sedimentary cover of the igneous intrusions would supply twice-weathered sands and silts for the Fox Hills and early Lance deposits, and the weathering of the igneous rocks might supply additional feldspathic materials for the Whitemud beds. The sands from the west might well mingle with the clays, causing the greater adulteration in this direction as noted by Davis. As erosion proceeded, the southeastern drainage might be re-established, as it apparently was, by early Oligocene time.

Since the above was first written, McLearn's "Stratigraphy, Structure, and Clay Deposits of Eastend Area, Cypress Hills, Saskatchewan,"[2] has been published. In dealing with the "Origin of Whitemud Sediments"[3] he discredits Davis' "extra-regional" weathering and pre-Cambrian source of the Whitemud sediments, and substitutes "intra-regional kaolinization or alteration" of sediments similar to those of the Estevan and Ravenscrag sediments and derived like them from the west. The explanation offered in this paper adds the possibility of additional feldspathic sediments from the Sweet Grass Hills volcanic area.

Fort Union time, apparently represented in the southwest by continuous deposition from St. Mary River to Willow Creek conditions, and by an erosion interval farther north, was an epoch of river sedimentation on swampy flood plains in the Cypress Hills–Boundary Plateau region. The Ravenscrag silts, sands, and peats were the result.

[1] See best reference: J. F. Kemp and Paul Billingsby, "Sweet Grass Hills, Montana," *Bull. Geol. Soc. Amer.*, Vol. XXXII, No. 4 (1921), pp. 437–78.

[2] *Geol. Surv. Can. Summ. Rept.*, Part B (1927), pp. 21–53.

[3] *Ibid.*, pp. 35–39.

Considering Fort Union as latest Cretaceous, transitional continental sedimentation continued in southwestern Alberta into Eocene time; erosion gave place to Paskapoo sedimentation north of Calgary; and erosion closed or followed the Eocene epoch in the Cypress Hills region, where no sediments of this time are known.

Reviewing the evidence, two uplifts in the Rocky Mountains are recognized. One occurred in late Pierre time, resulting in the widespread deposition of the transitional Fox Hills sandstone, followed by the fresh-water Lance sands, silts, and muds (St. Mary River, Estevan, Whitemud), the last of the sediments being perhaps included in the shales of the lower Willow Creek formation. A second or pre-Paskapoo uplift was more marked north of the Bow River, where it resulted first in an extensive erosion surface and later in the deposition of the Paskapoo sands and their southern extension, the upper Willow Creek sands and shales and the Porcupine Hills sandstone. The earlier uplift was clearly widespread in its effect, including, as shown, the Cypress Hills region, where the second was recorded in the deposition of the Ravenscrag sands, silts, etc. As suggested above, disturbances in the region of the Sweet Grass Hills may have modified the conditions prevailing in the Cypress Hills region, thus being responsible for the lack of sedimentation here while the upper Willow Creek shales and Porcupine Hills sands with their equivalent, the Paskapoo sands farther north, were being laid down in the west. A third uplift or the culmination of the second is recorded in the mountain border structure as seen in the disturbed belt which involves Willow Creek shales and possibly to a lesser extent the Porcupine Hills and Paskapoo sandstone. The Cypress Hills Oligocene conglomerate appears to owe its origin to this uplift; and so the close of the Laramide revolution is narrowed down to post-Paskapoo and pre-Oligocene time. The building of the Rocky Mountains may be thus dated as beginning with earliest Fox Hills time and reaching its final stage in Middle Eocene (post-Paskapoo) time.

The resulting gradients were sufficient during late Eocene time to cause the Cypress Hills region to be actively eroded. However, as the mountains in the west were worn down, large areas of quartzite formations were uncovered (probably Rocky Mountain quartzite),

and by early Oligocene time such loads of quartzite pebbles were dragged along the river beds of decreasing gradient that deposition resulted on flood plains in the region of the Hand Hills and Cypress Hills. One or more rivers heading in the mountains flowed eastward across the plains, maintaining a gradient of at least 15 feet per mile in the Cypress Hills region, over 200 miles from their source. Even with this gradient the coarse quartzite gravel was deposited on bars and flood plains, building up an important and resistant formation. Seventy or 80 feet of gravel mixed with sand was deposited, shingled (imbricated) toward the south and southeast, and decreasing in coarseness in the same direction. In its lower part the gravel is mixed with sediment derived from the underlying formations, here Fox Hills, there Whitemud, and more generally the Ravenscrag sands and silts. Upward the typical gravel has an uneven surface due probably to current action. An abrupt change of sedimentation, however, occurred as indicated by the clay mixed with gravel in the disconformable overlying beds, which contain mammal remains. The gradient of the rivers, too, decreased with time, for the gravel is replaced by grit and sand, which was piled over the gravel beds to a thickness of several hundreds of feet.

As so clearly stated by McConnell, the Cypress conglomerate evidently marks the course of an Oligocene river, with a gradient of about 15 feet per mile. The alinement of the conglomerate outcrops indicates a direction of flow toward the southeast, and this is borne out by the imbrication of the pebbles, the present slope of the formation, and an old stream channel which enters the Frenchman Valley above the mouth of Farewell Creek. The wide gravel-covered plateau north of Frenchman River evidently indicates a flood plain upon which a river or rivers debouched.

McConnell postulated a grade of 15 feet per mile all the way from the mountains in order to obtain sufficient current to carry the gravel. Alden[1] assumes for the 155 miles between the mountains at the international boundary and the west end of Cypress Hills a varying gradient as follows: 100 feet per mile in the mountains, for 5 miles; 75 feet per mile, for 10 miles; 40 feet, for 20 miles; 20 feet, for

[1] William C. Alden, "Physiographic Development of the Northern Great Plains," *Bull. Geol. Soc. Amer.*, Vol. XXXV (1924), p. 391.

20 miles; and 10 feet, for 100 miles—or 3,450 feet in all. The last estimate is less than that of the gravels, which averages about 15 feet per mile, and assumes a relative uplift in the mountains since Oligocene time. Alden's "projected grade reaches Chief Mountain about 200 feet below the top, or 8,850 feet above the sea. . . . . Farther south [it] would overtop the higher part of the smoothly worn crest of East Flattop Mountain (7,200 to 8,300 feet above tide) near lower St. Mary lakes."

The life of the Oligocene was as interesting as its river systems. In the rivers and lakes of the flood plains, lived ganoids, such as *Amia*, catfishes, a variety of turtles, lizards, and crocodiles, while in the adjoining swamps and on the uplands roamed herds of mammals including three-toed horses, huge titanotheres, various species of rhinoceros, giant swine, and piglike oreodonts, ruminants related to the tusked deer of the Old World, camels, rodents, and creodonts (primitive carnivores), besides many other forms. A well-developed Tertiary forest growth, probably of a mild climate habitat, is indicated by numerous specimens of fossil wood.

POST-OLIGOCENE HISTORY

Some time following the Oligocene river sedimentation, regional uplift occurred, and a great erosion plain was formed, which sloped gently eastward from the front of the mountains and coincided with the top of the Cypress gravels over wide areas. The age of this surface is believed to be early Miocene, and the uplifted remnants of the Cypress plain are recognized today in the Big Horn Mountains at an elevation of 9,000 feet, on West Butte at 6,300 feet, on the Cypress Hills at 4,800 feet in the west and at 3,500 feet near Eastend.

Further uplift rejuvenated the erosion systems, and a new land surface was formed below the Cypress plain, this being the Flaxville plain of Collier and Thom, which is probably of Lower Pliocene age.

Successive regional uplifts resulted in the formation of lower plains in late Pliocene(?) and early Pleistocene time. In the Cypress Hills, these are represented respectively by a bench 150 feet below the Flaxville plain and by the overdeepened valley of Battle Creek some 100 feet below the bench just mentioned. The preglacial surface was, as stated by Dawson, "rougher and more diversified" than the present surface. Its drainage system was more mature.

Over the dissected plain, the continental ice sheet advanced, planing off elevations and filling depressions, but flowing around the Cypress Hills and the Sweet Grass Hills. The mountain glaciers advanced rapidly with the refrigeration of the climate and spread out onto the plains before the slowly accumulating ice cap could move so far to the south. Later the Keewatin ice crowded down, met the mountain ice, and drove it back until Keewatin boulders were deposited well up on the fronts of the mountains. At this time, the two ice sheets flowed together to the south. Three times or more the ice advanced and retreated, and as it finally withdrew the rainfall and the runoff of the melting ice established a well-defined drainage system tributary to that of the Missouri River. The slope of the land was northerly; and so, on further retreat of the ice front, more northerly channels were excavated by the discharging waters. Thus an intricate system of dry coulees remains today as evidence of drainage adjustment during ice retreat. The south Saskatchewan system was finally established, as its lower channel was cleared of ice, and most of the Alberta drainage flowed into it. The valley of Milk River still remains, however, showing, by its perched position and unnatural drainage into the Missouri system through its 450-foot gorge, the results of the ice dam which so long prevented its normal northeasterly flow.

Postglacial time has seen a gradual development of modern conditions. The glaciers, by means of till and outwash deposits, built up a plain of deposition upon the somewhat dissected preglacial erosion plain, but left a drainage system incompletely adjusted to the regional slopes. Adjustment, mainly by the incising of rivers, has developed the modern system.

Weathering slowly changed the soft surface materials into soil, and plants gradually spread northward over sands, muds, and tills of the glaciated region. It is possible that the interglacial plant life of the plains was never destroyed on the Sweet Grass and Cypress Hills, as today their floras are closely related to those of the Rocky Mountains. Thus Douglas fir, *Pseudotsuga taxifolia* (Lambert) Britton, Jack pine, *Pinus contorta* Dougl., and western white pine, *Pinus albicaulis* Engelmann, grow on the Sweet Grass Hills, and spruce, *Picea engelmanii* Parry, and Jack pine, *Pinus contorta* Dougl., cover

considerable areas in the Cypress Hills. Macoun[1] concludes "Whether the Cypress Hills were an outlier of the Rocky Mountains or not, their flora indicated that their climate was that of the foothills above Morley. . . . . "

The typical North American Pliocene fauna disappeared with the advance of the continental ice sheets, although some forms still lingered in the unglaciated regions and about the ice fronts, following the ice back as it retreated during interglacial intervals and being driven ahead of it as it advanced. Examples are the horse, camel, one or more species of elephant, prong-horn antelope, musk ox, mountain goat, typical American deer (ancestors of Virginia, black tail, and mule deer), weasel, cougar, raccoon, squirrel, and probably some of the dog family. New Pleistocene genera appear to have come from Asia by a land or ice bridge across Bering Strait, including among them the moose, caribou, wapiti, bison, mountain sheep, wolverine, brown bears, mastodon, and some species of mammoth. The unglaciated areas of the Yukon Valley and other parts of Alaska and Yukon acted as a sanctuary for migrating animals, judging from the fossil remains found both in Alaska and Yukon. Other mammals, such as the beaver, are probably of Euro-Asiatic origin and migrated to America during either Pliocene or Pleistocene time.

With the passing of the ice age, the elephants, horses, and camels disappeared in North America, but other animals spread out over the glaciated area, as fast as verdure clothed the moraines and outwash deposits. The recent fauna consists of forms which by physical stamina and adaptation, and by mental ability, have survived the climatic changes, the restricted and crowded habitat, and other vicissitudes (probably including epidemics) resulting from the ice age. The survivors, especially among the mammals and birds, have increased greatly in numbers, reaching their maximum in the prehistoric epoch.

Southern forms are still making their way northward, as is seen in the northward migration of the pinnated grouse, which is marked within recent years. Life of the Upper Austral zone tends to make its way up the valleys of the Missouri River system, examples being the sage grouse, burrowing owl, and ornate horned toad. McConnell

[1] John Macoun, *Manitoba and the Great Northwest*, p. 192.

also reports the pocket gopher in the Cypress Hills. The rattlesnake occurs in the St. Mary River valley and the horned toad in Chin Coulee, both of which belong in reality to the Saskatchewan drainage basin, but were formerly part of the Missouri system, and are still connected with the Milk River valley by old channels. Both reptiles are found along Milk River. Dry climatic conditions are doubtless mainly responsible for the distribution of the semi-desert life, but its sharp boundaries, coincident with those of a former drainage system, are very suggestive of its migration routes. The annual migration of the former plains buffalo (*Bison bison*), following the ice north in the spring and retreating before it in the autumn, recalls the migrations of their Pleistocene ancestors as the ice retreated and advanced.

Man has been the last immigrant to occupy the plains, and his coming has brought entirely new factors to bear upon the distribution of plants and animals.

REVIEWS

The Earth, Our Ever-Changing Planet. By CHESTER A. REEDS. New York: University Society, 1931. (Distributed by the American Museum of Natural History.) Pp. 120; figs. 106.

Highlights of modern scientific knowledge are well presented. Seldom before has the vast scope of geology and its interrelations with the other branches of science been compressed into so readable a little volume. From the fascinating time-scale to the chapter on volcanoes, Dr. Reeds outlines the historical development and present state of geological thought lucidly and enthusiastically. A quantity of tabular data, in large part compiled by the author, marks the work as the result of no small effort. If Dr. Reeds has made his book too technical for easy assimilation by the non-scientific reader, nevertheless he has given the non-geological scientist a means of easy access to the outlines of modern geological thought.

RANDALL WRIGHT

"Geology and Water Resources in Parts of the Peace River and Grand Prairie Districts, Alberta." By R. L. RUTHERFORD. *Geological Survey Province of Alberta, Report No. 21.* Edmonton, 1930. Pp. 68; pls. 5; maps 3.

A complete discussion of the geology of this area is given as the result of a survey conducted primarily for the location of artesian-water horizons. This region is attracting settlers and an adequate water supply is essential, and for this reason the survey was undertaken. The stratigraphy and structure are well done, and P. S. Warren has added considerably to its value by his paleontologic work; the report contains an Appendix prepared by him describing and figuring new species in addition to the faunal lists embodied in the report.

J. T. McC.